Future Research Directions in Sustainable Mobility and Accessibility

A preliminary report by SMART
(Sustainable Mobility Accessibility Research and Transformation, a project of CARSS, Center for Advancing Research & Solutions for Society)
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Executive Summary

By 2020 over two thirds of the planet will be living in city regions. This has profound implications for how we think about and implement transportation in a world of accelerating globalization, congestion, climate change, demographic shifts (including aging populations), and social and economic disparity. Yet in many ways the research and knowledge base and the guiding theoretical frameworks for integrated urban transportation are not keeping pace with the call for immediate solutions in our rapidly changing cities.

This paper is initiated by SMART (Sustainable Mobility Accessibility Research and Transformation, a project of CARSS, Center for Advancing Research & Solutions for Society) at the University of Michigan. Currently SMART is working with several research partners, each bringing unique and complementary contributions that are central to understanding and addressing sustainable urban transport challenges and opportunities. SMART’s work, and this report have benefited from the support of a National Science Foundation Human and Social Dynamics (NSF-HSD) program to develop and catalyze systems-based research and to build a learning community focused on sustainable urban mobility and accessibility.

SMART’s aim with this report is to enhance existing research partnerships focused on sustainable urban transportation implementation by formalizing a collaborative research network that is propelled and enriched by regular annual workshops. This paper explores future research directions with the goal of supporting the development of the both the research collaborative and specific studies, as well as to inform broader research directions and policies.

Research topics included in this paper fall within the scope of sustainable transportation and accessibility in global urban regions. This may include moving people, moving goods, or moving less or any combination of the three elements. Research topics parallel SMART’s five key themes:

1. Systems Integration: Connecting the Dots for Analysis and Solution Building
2. The Accessibility Paradigm: Getting Ends and Means Straight
3. Supporting the Emergence of a Vital New Mobility Industry: New Roles for the Private Sector in Sustainable Urban Transportation (Public Private Innovation)
4. Socio-Cultural Context: Values, Aspirations, and Making Sustainable Transportation Hip and Attractive
5. Building Capacity for Now and for the Next Generation: Leadership and Education

In general the work of SMART includes analysis of the problem but gives greater priority to integrated solution development and implementation. In this way SMART’s research is informed by and informs its on-the-ground projects as well as its educational and Learning Community initiatives.
As part of an ongoing process to catalyze and support the development of SMART’s global research collaborative some specific examples of existing and future research directions that reflect the 5 key themes have been identified. The list is exemplary rather than exhaustive. It includes:

- Accessibility Indicators for Transportation Sustainability
- Developing New Business and Marketing Models for the Detroit Region’s Emerging New Mobility Industry Cluster
- Reducing Transportation Uncertainty for Urban Multimodalism and Emergency Response
- Measuring Climate Change Implications of New Mobility Hub Network Approaches based on Agent-based and Operational Location Analysis
- Predictive Life Cycle Assessment of Technology Designs for Sustainable Transportation in Urban Regions
- Accessibility as Transportation Equity
- Ensuring Robust, Resilient Urban Transport and Accessibility Systems in the Face of Uncertainty
- Comparative Evaluation of the Role of Status and Aspiration in the Design and Marketing of Integrated, Socially Equitable Transportation Systems in Three Selected Global Regions
- Evaluating the Influence of Urban Infrastructure on Sustainable Transportation and Accessibility Technology Diffusion
- Assessment of Light Weight Gas-Aluminum Composite Material for the Design of Stackable and Recyclable Plug-in Hybrid Electric Vehicles for Last Mile Urban Transportation Systems
- New Strategic Alliances: Artificial Intelligence and Agent-based Modeling Decision-Support Tools for Planning and Policy-making Related to Integrated Urban Transportation
- New Approaches and Designs for Sustainable Urban Mobility
In the course of developing this report, SMART also requested “Critical Analysis Papers” as well as “Systems Model Prototypes” from key research and project partners to provide supplementary detail on identified research topics, and to support recommendations on future research directions. These papers and systems prototypes are found in chapter 4 of this report.
I. Introduction

Rapid global urbanization has profound implications for how we think about and implement transportation in a world of accelerating globalization, congestion, climate change, demographic shifts (including aging populations), and social and economic disparity.

In response to these trends, urban transportation innovation is evolving worldwide, moving beyond the quest for silver bullet solutions and technical fixes towards more multi-faceted, connected, customized, practical, affordable, and systems-based solutions, and opening up entirely new solution spaces and markets. New services, products, transport modes, energy sources, technologies, and designs are connecting and converging in order to provide integrated and customized urban transportation portfolios that benefit society, the environment, and the economy.

Currently many of the most innovative sustainable transportation solutions are emerging in developing countries where the need can be most urgent, either because of rapid increases and demographic shifts in urban population, or as a result of recent economic growth and expansion. Innovative solutions are also emerging in the developed world, where the polluting and congesting effects of western development patterns directly affect quality of life and economic vitality in urban regions.

Yet in many ways the research and knowledge base and the guiding theoretical frameworks for integrated urban transportation are not keeping pace with the call for immediate solutions in our rapidly changing cities. As a result there is a growing need for international partners to pool their diverse and complementary strengths including research, innovation, technical expertise, on-the-ground experience, policy, and leadership and capacity building.

The purpose of this preliminary report is to begin to address the need for cross-disciplinary, collaborative international research that supports implementation of sustainable urban transportation. More specifically, it aims to:

- Support development of a global research collaborative,
- Support development of studies and overall research,
- Inform broader research directions and policies.

“Future Research Directions” is initiated by SMART (Sustainable Mobility Accessibility Research and Transformation, a project of CARSS, Center for Advancing Research & Solutions for Society) at the University of Michigan. Currently SMART is working with several research partners, each bringing unique and complementary contributions that are central to understanding and addressing sustainable urban transport challenges and opportunities. For example, amongst SMART’s current U.S. partners the University of Illinois at Chicago brings high level expertise in agent based modeling, urban ecology, and urban goods movement and logistics, Georgia Tech brings engineering capacity, and the University of Michigan brings a legacy of complex systems expertise as well as
strengths in social research, urban planning, and New Mobility industry development. Internationally, the Indian Institute of Management in Bangalore, India brings an innovative focus on business and public policy as well as rich academic and industry partnerships. The University of Western Cape in Cape Town South Africa brings a well developed ecological focus as well as transportation and planning expertise that is being applied by its leadership through significant university planning initiatives and skills training efforts. The Victoria Transport Policy Institute, Janaagraha, City Connect, and the Cambridge Program for Industry all bring a rich combination of engaged research and action.

SMART’s work, and this report, has benefited from the support of the National Science Foundation’s Human and Social Dynamics (NSF-HSD) program to develop systems-based research and to build a learning community focused on sustainable mobility and accessibility.
II. Acknowledgements

In the course of developing this report, SMART requested interviews, “Critical Analysis Papers” and “Systems Prototypes” from key research and project partners to provide supplementary detail on selected research topics, and to support recommendations on future research directions. SMART would like to acknowledge the following people who have contributed to this report. SMART’s work, and this report, have also benefited from the support of the National Science Foundation’s Human and Social Dynamics (NSF-HSD) program, as well as from Ford Motor Company and Royal Dutch/Shell.

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III. Examples of Future Research Directions

SMART’s aim with this report is to enhance existing research partnerships focused on sustainable urban transportation implementation by formalizing a collaborative research network that is propelled and enriched by regular annual workshops. This paper explores future research directions with the goal of supporting the development of the both the research collaborative and specific studies, as well as to inform broader research directions and policies.

Examples of future (and some existing) research directions outlined below are based on interviews with numerous experts in fields related to sustainable transportation along with proceedings from a meeting of sustainable transportation experts from academia, industry, government and non-governmental organizations (NGOs) organized by SMART in June 2008. The case studies and systems prototypes found later in this paper provide more detailed examples of potential future research topics.

Research topics are listed below in no particular order. Each topic falls within the scope of sustainable transportation and accessibility in global urban regions. This may include moving people, moving goods, or moving less or any combination of the three. Research topics are thematically distinguished as follows:

1. Systems Integration: Connecting the Dots for Analysis and Solution Building
2. The Accessibility Paradigm: Getting Ends and Means Straight
3. Supporting the Emergence of a Vital New Mobility Industry: New Roles for the Private Sector in Sustainable Urban Transportation (Public Private Innovation)
4. Socio-Cultural Context: Values, Aspirations, and Making Sustainable Transportation Hip and Attractive
5. Building Capacity for Now and for the Next Generation: Leadership and Education

Examples:

1) Accessibility Indicators for Transportation Sustainability

Transportation policy has traditionally focused on increasing travel speeds—or “mobility enhancement”— as a primary goal. In many regions in the United States and globally, this has led to an approach to transportation based primarily on infrastructure expansion. This kind of transportation planning has been implicated in problems of environmental degradation and social isolation. But most fundamentally, a focus on mobility as a transportation-policy goal neglects the consensus view that the vast majority of trips are not taken for the sake of movement per se, but in order to reach destinations, or more broadly, to meet needs. Mobility is thus properly viewed as a means to the greater ends of accessibility. But it is not the only means: accessibility can be enhanced through proximity, since being close to one’s destinations implies that they can be reached without great mobility. Accessibility can similarly be enhanced through electronic connectivity, which allows needs to be met remotely via phone, fax, or Internet. Transportation outcomes have largely been evaluated through mobility measurements,
such as travel speeds, congestion indicators, or highway level of service categorizations. This research stream would develop new alternative accessibility metrics for transportation-system evaluation, and would use these metrics to compare multiple metropolitan areas in the United States and other participating countries (Germany, Japan, China and South Africa). It would pay particular attention to the potential for remote connectivity as a strategy for accessibility enhancement, incorporating measures of the potential for remote connectivity (and attendant behaviors like telecommuting or teleshopping) into the index. The project would be geared at a reformed transportation practice oriented around accessibility enhancement. The accessibility perspective merges an urban planning view, which focuses on the impact of different patterns of land-use, with a sustainability approach to transportation, which seeks simultaneous pursuit of environmental, social, and economic goals. It builds upon research approaches from transportation, public policy and environmental science to develop improved analytical approaches and measurement tools.

Related subjects: planning, environment, and policy

Related research questions:
- What are the effects of land-use and specifically public schools on sprawl and accessibility?
- How do land use and transportation needs co-evolve? How do people’s preferences affect this co-evolution?
- What do individual travel patterns as tracked by GPS suggest about human behavior as related to transportation?
- Does the form of city/rural area development influence how and whether people take mass transit?

2) Developing New Business and Marketing Models for the Detroit Region’s Emerging New Mobility Industry Cluster

Michigan’s economic viability ranking as number 49 out of the 50 states is tightly tied to its ailing auto industry. Local communities are feeling the devastating effects of the shifting global marketplace. At one time Detroit was a world center of transportation innovation. But now a century after Henry Ford’s groundbreaking assembly line innovations and related new business models that offered car ownership to the masses, the region is faced with significant and complex urban and economic challenges, many of them ironically related to the automobile. At the same time, around the world new information technologies, services, products, and business models are emerging to support an increasingly sophisticated, multi-faceted approach to urban mobility, and a multi-billion dollar global market that is yet to be tapped. Developing a New Mobility industry requires a strong manufacturing base, advanced IT, an educated workforce, and a spirit of entrepreneurship – all emerging or projected strengths of the Detroit region today. It may also require new business models and changes in the public policy environment to support greater innovation and entrepreneurship. Linking economic development, planning, public policy, systems thinking, innovation and strategic alliances, this research stream would analyze market transformation precedents from
other industries. It would employ a range of methodologies including Stella system
dynamics models to develop a matrix of integrated business and marketing opportunities
for the development of a sustainable New Mobility industry (New MoTown) in the
Detroit region.

Related subjects: business, planning, policy, and strategic alliances

Related research questions:

- How can understanding successful strategic alliances be applied to the formation
of New Mobility hub networks, e.g. what are the qualities and characteristics of
successful alliances?
- What changes to institutional structure are necessary to allow for sustainable
mobility to occur?
- How does New Mobility affect employment and labor issues and opportunities?
- How can risk taking be encouraged in an industry that is as notoriously challenged
as the current automotive industry?
- What are the needs of industry from the point of view of information
infrastructure? How can it be made available? Is it better for this information to be
proprietary and owned individually or shared in an open access model?
- How are breakthrough innovations in large established businesses developed –
intrapreneurship?
- How does the private sector move appropriately into traditionally public sector
spaces such as transit?
- Where are there precedents / case studies of business / economic conversion e.g.
service to product, synergistic rather than single product?
- How can a company make money from system optimization or system synergy?
- How can industry work to support conducive public policy that accelerates New
Mobility implementation?
- What are the barriers to entry for entrepreneurs and what partnerships or other
opportunities would enable better success and integration?
- Bridging Collaborations-How is the gap bridged between the “urban planning”
approach to transit modes and the entrepreneurial, multimodal approach of Hubs?
- What are the prerequisites and winning conditions for innovation/ transformation
related to a New Mobility industry?
- Will business involvement in transport (mobility) increase or decrease
affordability?

3) Reducing Transportation Uncertainty for Urban Multimodalism and Emergency
Response

Transportation systems can be characterized both by "normal" or "average" operations
and by real-time operating characteristics at any moment. Day-to-day variability in
system performance can exact an especially high toll. For example a transit ride that is
long yet predictable may be deemed acceptable; one that is unpredictable may not attract
sufficient riders (even if it is quicker on average). Multimodal systems in particular rely
on dependable performance by the various modes; without this dependability, switching
between modes is impeded, as excessive margins of error need to be added to travel times to ensure that connections are not missed. Managing for day-to-day variability in transportation systems demands updated information on current system performance. But these real-time data alone are insufficient, because it is quick recognition of the deviation from usual performance that enables transportation system managers to respond. Methods for analyzing real-time transportation data (from sources such as inductive loop detectors in pavements, video detectors on poles and buildings, radar detectors, and road-side electronic permit/toll readers) jointly with static transportation-planning data on "typical" system performance are needed. Included in this research would be a joint analysis to develop new methods for quickly recognizing deviations to enable rapid response by transportation system managers or emergency responders. This research would merge a planning approach that focuses on static data and "typical" system performance with industrial and operations engineering.

Related subjects: engineering, planning, and telecommunications technology

Related research questions:
- How can network theory, e.g. understanding capacity of links, conservation of flow, and issues of timing, improve New Mobility hub network functioning?
- How can traditional design support and maintenance of industrial systems be applied to New Mobility hub systems to improve their performance?
- How can intelligent transportation systems and other advanced technologies impact New Mobility hub network performance?
- How can real-time transportation information technology be used to change the way we do strategic planning and implementation of New Mobility hub networks?

4) Measuring Climate Change Implications of New Mobility Hub Network Approaches based on Agent-based and Operational Location Analysis

New Mobility hub networks – a grid of nodes throughout a city where shifts happen between and across modes and services supported by information technology (urban ITS) – represent a new approach to providing sustainable urban transportation and accessibility. While to date much emphasis has been placed on sustainable fuel as the predominant and policy-supported route to sustainable transport, the fuel-based approach holds limited promise in a rapidly urbanizing world where the space and capacity for single occupancy motorization are diminishing. Linking social research, planning, business, and global studies, this research area identifies and explores comparative aspiration and status cues for integration into promotion of sustainable transportation and accessibility. It would employ diverse research tools including consumer surveys, human-subject laboratory experiments, and analysis of purchasing behavior in diverse social contexts.

Related subjects: systems modeling, ecology, and planning
Related research questions:

- What would it take to achieve a carbon neutral transport system?
- How can network theory, e.g. understanding capacity of links, conservation of flow, and issues of timing, improve New Mobility hub network functioning?
- How can traditional design support and maintenance of industrial systems be applied to New Mobility hub systems to improve their performance?
- How can intelligent transportation systems and other advanced technologies impact New Mobility hub network performance?
- How can real-time transportation information technology be used to change the way we do strategic planning and implementation of New Mobility hub networks?


Linking sustainability, engineering, and new businesses, this research stream would explore fuel cell design to help meet the environmental, policy and business challenges and opportunities of sustainable urban freight transportation. Modern vehicle systems have provided unparalleled personal and freight mobility that are essential to individual freedom, social interactions, market access and economic growth. However, the sustainability of such mobility has created serious challenges because (1) petroleum, which accounts for 96% of the total energy consumed for transportation, is finite in its reserve; (2) burning petroleum and other fossil fuels contributes directly to the emission of carbon dioxide and global climate change. Continuing to meet the mobility needs of society without causing irreparable damage to our environment is an imperative calling for technical and socio-economic solutions. One potential solution is a carbon neutral state where a range of sustainable energy sources are discovered, harvested and efficiently utilized to meet all of our mobility needs. Achieving this goal will require the development and innovative deployment of renewable fuels, including hydrogen produced from carbon-neutral sources, with advanced energy materials and suitable energy conversion and propulsion technologies. The range of propulsion options to be investigated will include fuel cells and fuel processors, ultra clean, electrified, high degree of freedom internal combustion engine technologies (like HCCI), and hybrid technologies (from mild to plug-in). In addition, the commitment of individuals and organizations to adoption of products incorporating these sustainable technologies and modified vehicle use patterns would be crucial. Linking sustainability, engineering and new businesses, this project would help to explore and meet the environmental, policy and business challenges and opportunities of sustainable transportation.

Related subjects: engineering, environment, planning, and energy

Related research questions:

- What is the real cost of fuel, e.g. look at all systems including climate change, wars, batteries, commuting, and what does the mean for the future of transportation?
- What new energy systems are best fit to fuel sustainable mobility of all types?
6) Predictive Life Cycle Assessment of Technology Designs for Sustainable Transportation in Urban Regions

Life Cycle Assessment (LCA) is a tool that evaluates the total emissions and environmental impact associated with the production, use, and fate of a product, process, or service. By definition LCA requires the existence of the product or technology already. Therefore LCA is not entirely applicable at the design stage of a process. For instance while a particular technology design (e.g., hybrid powertrain) might in theory increase fuel economy, the same technology might be used to increase acceleration with only modest fuel economy gains. Therefore the diffusion and manifestation of the technology depends entirely on market forces that must be included in the analysis method if we are to understand the true ramifications and possibilities for unintended consequences for a technology. Moreover, our method must understand not only how the technology will be used but also how much the technology will be used. For instance, to the extent that people with more fuel efficient vehicles drive more due to lower costs to drive per mile, a particular technology approach could have less improvement impact than original thought. This is the classic rebound effect. Developed at the University of Michigan, predictive life cycle assessment (pLCA) is a tool that can endogenously predict profit-optimal technology design applications and rebound effects. Like LCA, pLCA begins with goal definition and boundary setting activities. In pLCA an additional stage of “model definition” occurs: 1) to identify producer and consumer decision-making preferences, 2) to identify assumptions regarding technology availability, performance, and evolution, and 3) to identify models to be used for simulating market behavior. This research stream would further develop the methodology which links engineering, business analysis, systems modeling, policy research and design so that pLCA can serve as a core method for evaluating the quality of technological and policy approaches towards meeting the goals of SUMA.

Related subjects: planning, design, and policy

Related research questions:
- How can a systems view of materials used for New Mobility be used to inform material choices, e.g. lighter weight materials have CO2 benefits but are often harder to recycle?

7) Accessibility as Transportation Equity

Mobility-based transportation evaluations generally tend to focus on the transportation link as the relevant unit to be analyzed. Thus, transportation planners speak of the level-of-service (or freedom from congestion) of a particular stretch of highway. This approach creates the illusion that mobility benefits are spread uniformly across the population; after all, expensive and cheap vehicles all travel at the same speed under congested conditions. This approach neglects the fact that accessibility is distributed highly unequally...
throughout the population and depends on people’s location and access to transportation modes. The accessibility metrics developed in the previous research project could thus be used to analyze transportation equity: What kinds of land use patterns or transportation systems lead to greater equity in transportation access by income, race, age, or geography by focusing on accessibility as an attribute of individual households (rather than the mobility of transportation-system links)? Linking planning, social science, sustainability, and policy, this research stream would assess the effectiveness of a range of alternative equity-oriented transportation and land-use policy reforms.

Related subjects: social research, planning, and policy

Related research questions:

- Are the decision-making processes that determine funding and infrastructure placement influenced equitably across groups of people in ways that enhance the social equity of accessibility?
- Do New Mobility hub networks improve equity and accessibility in economically and politically risky areas that are otherwise accessibility poor?
- Assuming capitalism wasn’t invented to be an instrument of justice but efficiency, can business models aimed at serving the poor (the base of the pyramid population) be applied successfully to support sustainable and equitable transportation?

8) Ensuring Robust, Resilient Urban Transport and Accessibility Systems in the Face of Uncertainty

Urban systems that rely predominantly on a single mode of transportation for daily life and business provide little resilience and responsiveness in the face of unforeseen events, as recently witnessed in New Orleans and Houston. Damaged highways and paralyzing congestion caused by mass exodus of evacuees in cars risk cutting off access to emergency services and supplies. At the same time, auto-oriented infrastructure forces people without cars to walk long distances or to be isolated with no access to emergency care or security. Conversely, accessible urban systems operate much like backup energy distribution networks in the event of an outage, or meshed and re-routable information pathways that ensure consistent connectivity in the event of information break. Accessible systems prevent the risk of the “single point of failure” experienced in a Single Occupancy Vehicle (SOV)-dominated system. In the event of an emergency, the right mix of integrated multi-modal transport options, services, and information technologies combined with land use and urban design that favor human scale distances and safe and efficient access and egress can provide citizens, businesses, and emergency workers with a robust backup network of connected door-to-door alternatives to ensure safety and survival. Linking engineering, planning, environment, spatial analysis and systems modeling, this research area would integrate several modeling methodologies and network theories to understand how integrated, multi-modal, multi-service, multi-technology New Mobility and accessibility systems support robustness, resilience, and responsiveness to uncertainty, in particular to unpredictable disturbances such as abrupt
climate change, energy scarcities, network overloads, contagious diseases, violent weather, terrorist attacks and other acts of God in urban regions.

Related subjects: engineering, planning, spatial modeling, and systems

Related research questions:
- How do New Mobility hub networks and door-to-door multimodal multi-technology New Mobility support robustness, resilience, and responsiveness to uncertainty? How does this compare to the current SOV-dominant system?

9) Comparative Evaluation of the Role of Status and Aspiration in the Design and Marketing of Integrated, Socially Equitable Transportation Systems in Three Selected Global Regions

The personal automobile represents more than getting from A to B. It ties deeply to notions of culture, status, aspiration, and identity. And as the world urbanizes and gains increasing access to global media, the desire for motorized transportation rises exponentially both individually and politically. However notions of status and aspiration vary by culture. For example whereas in general in North America driving one’s own car is considered desirable, in India being driven around by someone else is preferred as an indicator of status or wealth. In stewarding a transition to sustainable urban transportation, it is essential to understand the underlying social and cultural significance of various transportation modes and practices both in order to design optimal, culture-specific systems, and to develop effective and compelling communication and marketing that reorients status and aspiration towards integrated sustainable urban mobility.

Linking engineering, planning, environment, spatial analysis and systems modeling, this research area would integrate several modeling methodologies and network theories to understand how integrated, multi-modal, multi-service, multi-technology New Mobility and accessibility systems support robustness, resilience, and responsiveness to uncertainty, in particular to unpredictable disturbances such as abrupt climate change, energy scarcities, network overloads, contagious diseases, violent weather, terrorist attacks and other acts of God in urban regions.

Related subjects: social research, planning, business, and global studies

Related research questions:
- How is mobility made easier and cheaper so that it’s not an altruistic decision for people to move out of individual cars?
- What is the effect of ephemeral events and word of mouth on people’s decisions to switch from car to bike or bus?
- How cultural aspirations and values be translated into new services, products, technologies, design and subsequently communicated and marketed compellingly
- It seems that one unique New Mobility solution will not work for all the mega cities of the world due to cultural, historical and other reasons. But can some basic principles be formulated that can guide the development of solutions unique to each mega-city? If yes, what are they?
• How can the perception that public transit is dangerous and not desirable be combated?

10) Evaluating the Influence of Urban Infrastructure on Sustainable Transportation and Accessibility Technology Diffusion

Linking urban planning, engineering, and social science, this research area would integrate infrastructure issues that clearly influence consumer preferences and then include this to understand technology adoption and optimal urban design. The acceptance and diffusion of more sustainable transportation technologies is strongly influenced by the characteristics of the urban regions in which these technologies are to be deployed. This was evident with the automobile, whose broad acceptance depended on the development of regions of ample roadways, parking facilities, service stations, and more. This research area would seek to identify and gauge the impact of those urban infrastructural reforms that can facilitate adoption of more sustainable transportation technologies. The predictive Life Cycle Assessment (pLCA) method forecasts technology diffusion as a function of consumer preferences and government policy. As it has been applied to date, pLCA has not considered the urban landscape and how that clearly influences consumer preferences. For instance, if an urban resident had access to a network of mobility services, would that resident buy the same car that she would have previously? Would she buy a car at all? What characteristics of the mobility network such as its accessibility, comfort, and transit times influence individuals to switch from single occupancy vehicles to multiple occupancy transit systems or other more sustainable modes such as walking or biking? What characteristics lead them to make travel reducing locational decisions? A primary difficulty here is developing an understanding of how social behavior changes as a function of different mobility choices and their accessibility.

Related subjects: planning, technology, engineering, business, and policy

Related research questions:
• How can the application of long-tail theory inform an understanding of adoption of New Mobility technologies?
• How do individual travel patterns correlate to environmental impact?
• Assuming it is difficult to know which segment will adopt new technologies and approaches ahead of time (and often what people want is dictated by what others want)-how does an understanding of product adoption and popularity- apply to adoption of New Mobility technologies?
• Can an understanding of micro-markets and spot-pricing using books and music as examples from other industries be applied to New Mobility hub network pricing?


As urban congestion increases it is becoming increasingly inefficient for commuters to
use SOVs. In many cases mass urban transportation strands commuters a short distance from their final destination. This is a major deterrent for transit commuters. Providing loaned mobility solutions for “last mile urban transportation” will not only enhance social acceptance and uptake of public transport by commuters and can work well within the hub network paradigm, increasing urban transportation efficiency. Plug-in Hybrid Electric Vehicles (PHEVs) provide a viable technology to facilitate “last mile urban transportation”. By using a combination of gasoline and electricity they cost less to operate and offer environmental benefits over gasoline vehicles. At the same time, vehicle-stacking technology can enhance implementation and value of this approach by conserving valuable urban space. A key design factor that affects fuel/energy economy and “stackability” is gross vehicle weight, which is largely governed by the materials used. Modern advanced materials offer reduced weight, while maintaining or improving their strength. One such material that is currently being adopted by automotive manufacturers is aluminum. It has a successful and sustained reputation as one of the most recycled modern materials because of the economic value of aluminum scrap. Moreover, only about 5% of the energy used to create the finished aluminum product from ore is required to produce the product from recycled aluminum. Modern aluminum composites provide increased strength at reduced weights, with close dimensional tolerances. This makes this metal ideal for use in PHEVs. In this research area, engineering students would be primarily exposed to the trade-off between the environment, urban and social impact, and viable engineering problem solutions. They will analyze a range of design decisions related to advanced materials, joining and design techniques in terms of meeting the challenges of complex urban transportation. They would also develop analytical and/or numerical models to investigate the technical as well as business feasibility considering the constraints in environment, economics, and consumer behaviors. This research stream would elucidate how innovative business models, urban policies and society can together impact the adoption of new technologies and vice versa.

Related subjects: engineering, business, and planning

Related research questions:
- Can the Bass model be used to gain an understanding of Hybrid or Plug-in hybrid adoption?

12) New Strategic Alliances: Artificial Intelligence and Agent-based Modeling Decision-Support Tools for Planning and Policy-making Related to Integrated Urban Transportation

An increasingly complex urban transportation context implicates a widening range of players and sectors in identifying and delivering appropriate and sustainable systems and solutions. Whereas urban transportation has traditionally been considered “public realm”, new and more proactive roles are evolving for the private sector, NGOs, academe, and labor, in concert. Even within the public sector, a wider range of departments and agencies are becoming involved. As such new decision making tools are needed to support the collaboration and strategic alliances necessary for effective and integrated
urban transportation. New visualization, assessment and analysis tools are required to inform decisions that simultaneously involve a range of players and goals linking technology, engineering, design, and policy, this research area will identify and evaluate and integrate existing decision making tools and develop new technologies to support whole systems decision making related to sustainable urban transportation and accessibility. Linking technology, engineering, design, and policy, this research area would identify, evaluate, and integrate existing decision making tools as a foundation for the development of new integrated tool sets that facilitate whole systems, real-time visualization decision making related to sustainable urban transportation and accessibility.

*Related subjects:* technology, engineering, design, and policy

*Related research questions:*
- Can a rebound affect of hub network growth be predicted and reduced with policy measures?
- What decision-making tools can be used to inform urban transportation?
- Should governments be rethinking subsidies to encourage accessibility over mobility?
- How can government standardization lead to greater accessibility and sustainable mobility?
- How do we inspire leadership in cities where it doesn’t yet exist?
- What are the key indicators for cities with high non-automobile mobility? Is there good quantification data that shows the relative importance of those indicators?
- How can New Mobility support political requirements but be enabled to be longer term than political terms?
- What strategies for increasing security related to public transit can be applied to New Mobility hubs and vice versa?
- How do we increase public demand and support for government investment in New Mobility?

13) **New Approaches and Designs for Sustainable Urban Mobility**

- How can the New Mobility industry capitalize on the trend of dynamics and customization of system, service, community, and product design?
- What other bio inspired designs could evolve from collaborations between schools of Engineering, Life Sciences, Urban Planning, etc?
- Women’s travel needs differ from men’s—is gender and income level taken into consideration in New Mobility hub network design? Are women of low-income status consulted?
IV. Critical Analysis Papers and System Model Prototypes

Jeff Adik: “Sustainable, Integrated, Urban Mobility: Research Topic Recommendations”

Jay Agopi: “Evaluating congestion pricing through system dynamics”

Dr. Lisa Aultman-Hall: “Integrated Frameworks for New Mobility: From Northern Rural Landscapes to International City Regions”

Avik Basu: “Motivating SMART”

Eric Britton: “Priority Research Directions in New Mobility 2008-2012” and “The New Mobility Knowledge Environment”

Kevin Clemens: “Personal Mobility and Global Climate Change”

Dr. Tom Gladwin: “Mega-Challenges Confronting Sustainable Urban Modernity”

Krista Gullo et al.: “A Model of Social Inequity and Accessibility in Detroit”

Dr. PJ Lamberson: “The Diffusion of Hybrid Electric Vehicles”

Matthew McMurtry and Annie White: “The Robustness of Scale Free Networks” and “New Mobility Hub Networks and Rebound Effects”

Dr. Irv Salmeen: “Innovating for New Mobility”

Sue Zielinski: “New Mobility: The Next Generation of Sustainable Urban Transportation”
An Exploration of Research Topics  
Designed to Support the Viable Business Opportunities surrounding Sustainable Integrated Urban Mobility 

Jeffrey Adik; Founder/Chairman; Intraduce Transit, LLC 
July 22, 2008

The recent development of concepts surrounding Sustainable Integrated Urban Mobility has opened the door to a broad range of questions surrounding systemic economic viability. There are many approaches to mobility that expose relevant and significant opportunities for integration within such a framework. At a high level, however, it is an array of complex accessibility and mobility strategy permutations that do not clearly define an optimal business development roadmap. Nor does this list directly provide an obvious prioritization approach, schedule of implementation or an analysis of resulting economic and environmental upside.

The dynamic nature of the urban community’s population density, economic investment and prosperity, aesthetic flavor, political fluidity and cultural heterogeneity (amongst other things), are the direct result of society’s incrementalist efforts that have delivered cause-effect based results. Various transportation approaches that fall within the ‘New Mobility’ and ‘Sustainable Integrated Urban Mobility’ framework are often highly supportive of organic expansion driven by need and opportunity. When analyzed within controlled environments, these approaches share unique stories explaining their combined effect within the system of observation.

Organic growth often delivers new problems that manifest from a lack of planned priority, holistic systemic awareness and integrated function. Within the dynamic complex context of the urban community, it may not be clear what results will occur when one or more approaches are implemented within the mobility framework. If we are to pursue continuous improvement and steer the future of our communities toward sustainable prosperity, it is essential that we begin to coordinate tools that provide a starting point for understanding the impact of these approaches across the array of strategy permutations, each with unique interactions and manifestations.

While some tools exist to appropriately evaluate business opportunities for discrete approaches, there is no clear evidence of a tool that serves to assist in the space of the identified need. Specifically, an analytical tool is being requested that provides the Sustainable Integrated Urban Mobility community with the web-enabled ability to easily:

- Identify a need for research specific to a clearly defined approach,
- Support the aggregation of this research (across industry, academia and government), and
- Provide a framework for the integrated analysis of the solutions,
- Project the effects of approach combination through
  - scale of implementation and
  - temporal prioritization.
From an entrepreneur’s perspective, it is recommended that the list of primary research topics include:

1. An annotated listing of the unique types/approaches of transportation integration that should be considered
2. Establishment of attributes that address how well each transportation approach is aligned with Sustainable Integrated Urban Mobility
3. A listing of geographic locations, with
   a. An associated mobility/accessibility index
   b. Regional micro-economic GDP by industry category
   c. Other market and labor based topics of consideration
4. A preliminary prioritized list (based on attributes specific to perceived influence on economic prosperity and quality of life) including:
   a. The independent types of transportation to be analyzed,
   b. The entire permutation of transportation approaches

It is further recommended that a detailed research analysis be performed on:

1. Each discrete transportation element, and subsequently
2. The prioritized list of permutations that combine transportation approaches.

The research analysis for this list should be coordinated to deliver:

1. The short and long term financial impact, and quality of life impact surrounding:
   a. Traditional Transit Oriented Development
   b. Accessibility Oriented Development
2. The discrete micro-economic GDP growth impact potential on an industry categorized level. (A coefficient or multiple that addresses the economic feedback loop generated: e.g. House Committee on Transportation identifies Transit generates a 1:6.2 economic impact to a region through job creation, direct and indirect investment)
3. An urban density & accessibility coefficient/descriptor that explains the influence of the approach over time (this may be represented by a polynomial equation that integrates variables such as geographic area, existing population density, forecasted population change, time, etc.)
4. The permutation’s synergy index. (How the ‘combined’ effect of the associated transportation approaches is greater than simply the sum of the impact created by each individual approach). This may be considered to be an acceleration vector, which suggests a compounding effect, and probably calls for a second order differential to explain accurately
5. The general qualitative impact created within the urban community
6. The portability of the approach based on regional factors including (but not limited to):
   a. Geographic location, shape, and global accessibility
   b. Cost of labor, cost of living and CPI
   c. Regional Climate
   d. Elements of cultural significance related to mobility and accessibility, including:
      i. Social class structure and tolerance
      ii. Economic diversity and tolerance
      iii. Racial diversity and tolerance
      iv. Religious diversity and tolerance
      v. Gender equality, and tolerance
      vi. Political stability, influence, and influence to suffrage
Evaluating congestion pricing through system dynamics

Sathyanarayanan Jayagopi

Abstract:

Almost all large cities in the world face the problem of traffic congestion. In recent years a number of policies have been developed to reduce congestion. One such policy to reduce congestion is an area wide congestion pricing scheme. On Feb. 2003, London became the first city in the world to implement this scheme. However, many people perceive this as a tax, hence the political acceptability of this scheme depends primarily on how the revenue from the congestion pricing scheme is recycled. The most common revenue recycling options are: reducing general tax, reducing fuel price by reducing fuel tax, increasing highway capacity or building more roads and increasing public transit service. The system dynamics model described in this paper evaluates the effect of congestion pricing, all the four policy options and the offsetting changes in human behavior or the ‘rebound effect’ of those policy options on congestion cost. In order for congestion pricing to be highly effective in the long run two conditions must be met: 1) revenue obtained from congestion pricing must be used to expand public transit service and 2) the area of the city under the congestion pricing scheme and congestion price should be increased periodically. Also, congestion pricing is an effective tool to reduce CO2 emissions from urban transportation.
**Introduction:**

Most of the large cities in the developed world witnessed a substantial increase in car ownership and declining market shares of public transit system over the last two decades resulting in a rapid increase in the use of privately owned automobiles for road travel. For example, in the US car ownership has risen from around 600 per 1000 persons in 1980 to around 750 per 1000 persons in 2001. Whereas the public transit share of total number of trips has declined from 5.9 percent in 1983 to 4.7 percent during that period (WBCSD mobility report, 2001) and (Downs 1992, 2004). Similar patterns of increasing car ownership and declining public transportation shares as a percent of total trips are beginning to emerge from many cities in the developing countries.

As a consequence of this increasing car ownership, almost all large cities are experiencing rising road congestion. In the US, an average traveler in an urban area spends 47 extra hours per year in travel compared to 40 hours in 1993 (TTI congestion report, 2005). As a result, many policymakers are exploring different strategies for reducing congestion. There are several strategies for reducing congestion which can be broadly classified into two types: 1) supply side strategy such as building more roads, using more high occupancy lanes or building additional public transit capacities and 2) demand side management such as shifting peak hour trips to other time of the day, encouraging ride sharing, raising the cost of parking or congestion pricing.

This paper seeks to explore the possibility of using congestion pricing as a tool to reduce congestion, and in particular seeks to explore whether it is possible to reduce congestion significantly in the long run and what are necessary policies that have to be in place in order to reduce congestion through congestion pricing.

**Congestion:**

Congestion is relatively easy to identify by such telltale examples as roads filled with cars and trucks and buses moving at a very slow pace. The dictionary defines congestion through words such as “clog” and “abnormal” or “excessive accumulation”. Traffic engineers define congestion as a situation that arises when the total input traffic volume in a facility exceeds the designed maximum capacity of that facility. As the input traffic volume raises so does the density of vehicles i.e. the number of vehicles per lane mile of the facility. As the vehicular density increases beyond a certain threshold limit, speed decreases because of vehicle closeness. The resulting speed is very much slower than the normal or free-flow speed. And, when vehicles are bumper to bumper, a highly undesirable “stop and go” traffic condition is often experienced.

There are basically two types of congestion. They are recurring and non-recurring congestion. The former is the type of congestion that occurs routinely at the same place and same time especially during the peak hours of the weekdays. The later arises because of random events such as accidents, temporary road work or vehicle breakdown. Recurrent congestion primarily arises for two reasons. First, during peak hours (i.e. morning and evening) travel demand is at a maximum because most workers are following very similar work schedules. Secondly, recurrent congestion arises because of bottlenecks in the roadway system. Bottlenecks are locations where the traffic inflow to a particular facility is very much higher than the capacity than the particular facility can handle. (Stopher, 2004).
Since recurrent congestion is a systems problem caused by habitual driving patterns of people and highway system constraints, reducing recurrent congestion is the principle focus of congestion reduction strategies. This paper will focus on using congestion pricing as a tool to reduce recurrent congestion.

**Causes of congestion:**

The main causes of recurring peak hour congestion are rapid growth in population, jobs and the economy; travel behavior patterns and choice; and desire to live in low density settlements.

**Rapid population, job and economic growth:**

Growth in population, job and economic activity in a region will inevitably increase the daily traffic flow within a region. Between 1990 and 2000, population in metropolitan regions of the US grew by an average of 13.1 percent. Along with this population, growth employment grew by 13.8 percent in the US (Downs, 1992, 2004). This means that along with population growth, more workers are commuting daily. Employment growth increases the GDP per capita income over time. As income increases people tend to increase the distance that they travel roughly in proportion to the increase in their income. Moreover, they prefer faster modes of transportation, mainly selecting privately owned automobiles (WBCSD mobility 2001). Hence, rising population, employment and economic activity increases the number of vehicles and the distance they travel by road, which increases congestion.

**Travel behavior pattern and choice:**

Most of the institutions and organizations have approximately the same working hours daily in order to have high productivity. This causes millions of people to travel during the hours of 6:00-9:00 in the morning and 4:00-7:00 in the evening – the so called “peak hours”. The net effect of this high trip concentration is that the traffic inflow exceeds the designed capacity of many highways and intersections thereby creating bottleneck conditions which in turn result in congestion. Moreover, most people prefer using privately owned automobiles for their daily trip because of the privacy and convenience they offer (Nasser, 2002). In the US, during peak hours, 87.9 percent of workers commuted in privately owned automobiles in 2000 whereas only 4.7 percent of workers used some form of public transit for their commute. Moreover, 75.7 percent of all commuters traveled singly in their vehicles (Downs, 1992, 2004). This preference for using privately owned vehicles for trips immensely increases the total number of vehicles on the road which in turn increases congestion.

** Desire to live in low density settlements:**

A goal of most American households is to live in a one single family home with private open space next to each dwelling. This American dream has two major adverse effects which increase traffic congestion. First, it reduces the population density, which makes it difficult for a public transit system to provide adequate service. Secondly, it increases the average commuting distance between workplace and home (Downs, 1992, 2004). Moreover, people while choosing their home location do not consider commuting distance or time as a major factor while make decision on house location. (Scheiner et al, 2003).

**Effects of congestion:**

There are two main effects of traffic congestion. First, individual vehicle’s average speed in congestion
is much lower than the average free flow speed, requiring extra time to travel under congested conditions. This lost time or delay during peak hours in traffic congestion results in lost working hours, which in turn results in loss to the GDP. Secondly, in congested traffic conditions, vehicle engines operate at lower speeds reducing their fuel economy. Hence more fuel is consumed and more pollutants are released in traffic congestion conditions. The system dynamics model described in this paper uses the Texas Transportation Institute (TTI) methodology for calculating total cost of congestion imparted on the society. The total congestion cost in this model is the sum total of average delay cost and the cost of fuel wasted in traffic congestion. However, the true cost of traffic congestion is much higher than the cost of congestion obtained through TTI methods since some of the other effects of traffic congestion are not taken into consideration which are:

**Increased stress while driving in congested conditions:**
Increased congestion on road often results in stop and go traffic conditions which frustrate the drivers and increase there stress level. Sometimes in congested conditions drivers tend to make mistakes and use impolite driving maneuvers which leads to angry reactions from other frustrated drivers. Psychiatrists call this type of behavior as “road rage” or Intermittent Explosive Disorder. It is expected that up to 16 million adults in America are affected from this type of disorder (CNN, 2006). Also, frustrated drivers often drive aggressively, ignore red lights and stop signs and frequently change lanes which not only risks their life but also of there fellow passengers, drivers and pedestrians on road.

**Air pollution:**
The most obvious environmental impact of congestion is air pollution. In congested condition vehicles move at speeds which are much lower than their normal speed, or in some conditions operate in ‘stop and go’ traffic conditions. Vehicle engines are primarily not designed to operate under these conditions hence there efficiency will be quite low and more fuel will be consumed and along with that more of harmful pollutants like CO2, nitrogen oxides and volatile organic compound will be released. Unlike thermal power plant pollutants which have lower effect on humans because of their remote location, air pollutants from automobile have high proximity to humans hence this causes adverse impact on human health such as respiratory disorders and eye irritation. Moreover, transportation is one of the major sources of Green House Gas emissions like CO2 and traffic congestion would inevitably increase the emission of CO2 from transportation.

**Noise pollution:**
Drivers in congested roads frequently press horn and apply break which increase the noise level in the adjoining area of the congested road. Noise pollution adversely effects human hearing, causes sleep loss, increases stress and distraction and reduces the quality of life.

**Effect on non motorized transport and social equity:**
Increasing traffic volume on road reduces the safety and comfort of people who prefer walking and cycling for personal transportation. This reduces the viability of those modes and forces them to use vehicles for transportation. Transportation experts refer to this effect as barrier or severance effect (VTPI, 2005). Also, increase in traffic congestion on roads reduces the reliability of public transit systems operation which adversely affects those people who rely on public transit system.

**Congestion pricing:**
Transportation economists argue that the reason for congested roadways during peak hours is that although a person driving on congested roadway is adding to the collective cost by increasing delays for himself and others, he is not required to pay the for the full loss created by his behavior. In the absence of any price and toll, more and more drivers may enter the roadways causing additional loss to society. Economists call this problem the “external effect” or “the externality”. The proposed economic solution for this problem is to impose a corrective tax that each driver has to pay for the loss that he imparts on society. One such possible corrective policy measure to reduce the externality is congestion pricing.

Congestion pricing increases the price of travel during the peak travel hours which could reduce the demand for travel i.e., the number of cars on road. There are a number of different mechanisms through which congestion pricing can be imposed. For instance, mechanisms could provide for the imposition of tolls on specific sections of highways, distance based charging or the area wide scheme in which drivers have to pay when they cross a cordon area or zone during the peak time period.

In February 2003, London became the first city in the world to implement an area wide congestion pricing scheme for the central area of London, to reduce peak hour congestion. A car entering the pricing zone between 7:00 am and 6:30 pm, Monday to Friday, was charged £5. The immediate effect of this pricing scheme was that the congestion within the charging zone was reduced by 30 percent and subsequently the ridership of public transit system increased by 38 percent. (Ferrari, 2005). On 4 July, 2005 the congestion charge was increased to £8 and from 19th February 2007, the pricing zone would be expanded westwards which would include Chelsea and some parts of Westminster. Many other cities around the world are considering similar scheme to reduce congestion. However most people view congestion pricing as a tax, hence like all other taxes, political acceptability of congestion pricing mainly depend on the revenue disbursement or the tax recycling policy of the scheme (Small, 1992).

Even though congestion pricing improves the economic efficiency of the situation, in general most users are worse off with the congestion pricing, except those who have a very high value for travel time. Moreover, like all other taxes, it is considered by many to have a regressive effect and its distributional effects are unclear. (Layard, 1977), (Foster, 1975), (Guilaino, 1992).

Hence, in order for congestion pricing to be politically acceptable, some economists suggest that the revenue from congestion pricing be returned to motorists in the form of lower fuel duties. (Newbery 1990, 1994), (Livingston, 2001). While, some suggest that revenue from congestion pricing should be used to reduce the distortions created by labor taxes, which would reduce the dead weight loss of the tax system by encouraging labor force participation at the margin. (Parry et al, 2001). Goodwin proposes an arbitrary system in which revenues are equally allocated to 1) reduce taxes in the system like fuel tax or vehicle license fee 2) on new road construction and 3) the public transit system. (Goodwin 1989)

The model developed in this paper evaluates all these revenue distribution options, along with the changes in the human behavior associated with these options, i.e., the so called rebound effect of these options and its effect on the total congestion cost in the long run.

**Rebound effect:**
A rebound effect or offsetting behavior refers to increased consumption that result from action which
increases efficiency and reduces consumption cost (Herring, 1998). Rebound effect can be explained by a simple microeconomic theory – the law of demand, which states that demand is inversely proportional to price if other variables such as population, price of competing goods and services and consumer preference are constant. Hence, any policy or technology which reduces in terms of price, time or discomfort would inevitably increase consumption. This offsetting behavior of consumer would greatly reduce the overall goal of efficiency gain of any policy or technology.

In the field of transportation, the most common offsetting behavior or rebound effects are- 1) Generated traffic or road induced traffic which is the additional vehicle travel that occur because of improvement in highway capacity which reduces time and cost of travel. (Hansen, 1995), (Noland, 2001) (Cervero, 2003) 2) Improved fuel efficiency gain which reduces per vehicle mile operating cost but increases per vehicle annual mileage (Greene et al, 1999).

Model:

General Structure:
As the population and economic activity in a region increases, the number of vehicles on the roads and the average per capita miles traveled increases in that region which in turn increases congestion. In order to mitigate traffic congestion, an area-wide congestion pricing system may be introduced. The revenue generated from congestion pricing is recycled back to the society. The model discussed in this paper primarily consists of five loops (figure 1): three reinforcing and two balancing. The three reinforcing loops are: a Building More Roads loop, a Lowering Fuel Prices loop and a Per Capita Income Driving loop. The balancing loops are: a Congestion Pricing loop and an Increasing Public Transit Expenditure loop.

Since the objective of this model is to evaluate congestion pricing and the congestion price revenue recycling policy of the government, population growth and the economic activity in the region which increases per capita income are considered as exogenous variables. Also, the model assumes that road networks and traffic volume are uniformly distributed within the city. The model discussed in this paper was developed using STELLA version 9.0.
Causal Loop Diagram:

Growing Population

Increases Public Transit Ridership

B1: Congestion Pricing Loop

Car use reduction

CARS on Road

Traffic Volume

VMT

Average Delay

Total Congestion Cost

Increases Travel Cost

Congestion Pricing

Increases Public Transit Services

Revenue from Congestion Pricing

Redistribute revenue to Population

Build More Roads

Driving Growth

Road Induced Driving

Road Growth

R2: Lowering Fuel Price Loop

Low Fuel Price

Induced Driving

Reduce Fuel Price

Economic Growth

Per Capita Income

R3: Per Capita Income Driving Loop

Fig 1: Causal Loop Diagram
Model Assumptions:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Population commuting during peak hour:</td>
<td>10,000,000</td>
</tr>
<tr>
<td>Population Growth rate:</td>
<td>Initial growth rate 1.8%; Growth rate declines gradually; after 20 years 1%;</td>
</tr>
<tr>
<td>Initial percentage of population using public transit:</td>
<td>15%</td>
</tr>
<tr>
<td>Modes of transportation:</td>
<td>2 (Public and Private)</td>
</tr>
<tr>
<td>Average occupancy per vehicle:</td>
<td>1.25</td>
</tr>
<tr>
<td>Initial average miles driven per car per day during peak period:</td>
<td>20 miles</td>
</tr>
<tr>
<td>Initial freeway lane mile:</td>
<td>3500 lane mile</td>
</tr>
<tr>
<td>Principle arterial lane mile:</td>
<td>9500 lane mile</td>
</tr>
<tr>
<td>Normal lane mile growth rate:</td>
<td>1%</td>
</tr>
<tr>
<td>Cost of building freeway per lane mile:</td>
<td>$ 10,000,000</td>
</tr>
<tr>
<td>Cost of building arterial road per lane mile:</td>
<td>$ 2,000,000</td>
</tr>
<tr>
<td>Percent of road expenditure allocated to freeway expansion:</td>
<td>75%</td>
</tr>
<tr>
<td>Percent of VMT in freeway:</td>
<td>47%</td>
</tr>
<tr>
<td>Percent of VMT in arterial roads:</td>
<td>53%</td>
</tr>
<tr>
<td>Inflation rate:</td>
<td>2.5%</td>
</tr>
<tr>
<td>Base fuel price:</td>
<td>$3 /gallon.</td>
</tr>
<tr>
<td>Initial per capita income:</td>
<td>$26,000.</td>
</tr>
<tr>
<td>Per capita income growth rate:</td>
<td>3.0%</td>
</tr>
<tr>
<td>Number of working days:</td>
<td>250</td>
</tr>
<tr>
<td>Daily hours of working:</td>
<td>8</td>
</tr>
<tr>
<td>Initial public transportation service expenditure:</td>
<td>$ 950,000,000</td>
</tr>
</tbody>
</table>

Measuring Traffic:

Traffic engineers measure traffic volume in vehicle miles traveled per day or Daily Vehicles Miles Traveled (DVMT). DVMT is the product of number of vehicles on road in that region and the number of miles each vehicle travels during the peak period. The number of cars on the road per day is determined from the population, percentage of population using cars for daily transit and the average occupancy of each vehicle.
Percentage of population using car for transportation = 100 – percentage population using public transit

Numbers of Cars = (Population * percentage population using car)/Average vehicle Occupancy.

Average Daily Vehicle miles traveled (DVMT) = (Number of Cars on road daily * Average Miles driven per car during peak period)

**Methodology for measuring Total Congestion Cost:**

The main effect of congestion is that it decreases the average speed of vehicle movement in traffic which in turn increases the time spent on road which could have otherwise be used for some productive work. Also, vehicles traveling at lower speeds are less fuel efficient hence more fuel is wasted in congestion.

The model used in this paper employs the Texas Transportation Institutes methodology of measuring congestion cost which sums the delay cost and the cost of fuel wasted in congestion. Traffic congestion also presents other problems which will not be considered in this paper such as increases in the stress level of drivers, road rage and increased emission of more criteria pollutants like volatile organic compounds and carbon monoxide by vehicles traveling at low speeds. The following steps are involved in calculating the Total Congestion Cost: (TTI, 2004)

1. Obtain the Average DVMT for the peak period.

2. Identify the percentage of peak period travel in congested time:

This is determined by the Roadway Congestion Index (RCI). RCI is used as an indicator of the number of hours of the day that might be affected by congested conditions.

\[
RCI = \frac{((\text{Freeway VMT}/\text{lane mile}) \times \text{Freeway VMT}) + ((\text{Principle arterial VMT}/\text{lane mile}) \times \text{Principle arterial VMT})}{(14000 \times \text{Freeway VMT}) + (5500 \times \text{Principle arterial VMT})}
\]

Freeway VMT = Average Daily VMT * Percentage of VMT in Freeway
Arterial Road VMT = Average Daily VMT * Percentage of VMT in Arterial Road.
Percentage of Daily VMT in Congested time = \( f(RCI) \)

Figure 2 was used to estimate the percent of daily travel in congested time.

![Figure 2. Percent of daily travel in congested time.](image)
Daily VMT in Congested Time = Percentage of Daily VMT in congested time * Average Daily VMT

3. Determine the Congestion Level on Freeway and Principle Arterial road:

   Congestion level is based on the Average Daily Traffic (ADT) Volume per lane. ADT is determined by dividing the VMT by lane-miles for each congestion level.

   Freeway ADT per lane = \(\frac{\text{Daily \_VMT\_in\_Congested\_Time}}{\text{Freeway\_Lane\_Mile}}\)

   Arterial road ADT per lane = \(\frac{\text{Daily \_VMT\_in\_Congested\_Time}}{\text{Principle\_Arterial\_Lane\_Mile}}\)

4. Determine the speed of the traffic using the speed estimation curve:

   Average speed = \(f(\text{Average ADT per lane})\)

Figure 3 and 4 were for estimating the average speed during congested time on Freeway and Principle Arterial Road, respectively. Only combined direction speed curve was used for speed estimation.
5. Determine the delay caused due to congestion:

The difference in the amount of time it takes to travel the peak-period vehicle-miles at the average speed and at free-flow speeds is termed delay.

\[
\text{Average Delay} = \frac{\text{Daily VMT in Congested Time}}{\text{Average speed in congestion}} - \frac{\text{Daily VMT in Congested Time}}{\text{Free Flow Speed}}
\]

\[
\text{Average speed in congestion} = (\text{Percentage in Freeway} \times \text{Freeway speed Estimated}) + (\text{Percentage travel in Arterial Roads} \times \text{Arterial Speed Estimated})
\]

Free Flow speed = (Percentage in Freeway*60)+(Percentage travel in Arterial Roads*35)

Freeway free flow speed = 60 miles per hour; Principle Arterial Free flow speed = 35 miles per hour.

6. Determine Annual Passenger Vehicle Delay Cost:

\[
\text{Annual Passenger Vehicle Delay Cost} = \text{Average Delay} \times \text{Average hourly income} \times \text{Average Vehicle Occupancy} \times \text{Number of working days.}
\]
Average hourly income = (Annual average per capita income)/(Number of working days * 8)

Daily hours of working = 8

7. Determine the annual cost of fuel wasted:

Average fuel economy in congestion = 8.8 + ( 0.25 * Average Speed in Congestion) \hspace{0.5cm} (Raus J., 1981)

Annual fuel wasted in congestion = \( \frac{(Average\_delay*Average\_speed\_in\_congestion)}{(Average\_Fuel\_Economy\_in\_congestion)*Number\_of\_working\_days} \)

8. Determine the Total Congestion Cost:

\textbf{Total congestion cost} = (Cost\_of\_Annual\_Fuel\_wasted+Annual\_passenger\_vehicle\_delay\_cost)

\textbf{Congestion Pricing Loop:}

Most transportation economists perceive travel as a derived demand. Like all other demand functions, one can assume that there is a downward sloping demand curve for travel. Hence, if the price of travel is increased then the demand for travel would decrease. Implementation of a congestion pricing scheme would effectively increase the price of travel for some beyond their willingness to pay. Hence, after the implementation of congestion pricing there will be a decrease in the daily number of cars on the road since those drivers affected by congestion pricing would choose public transit for transportation, thereby resulting in new equilibrium between public and private modal share.

Decrease in number of cars on road due to congestion pricing = (Cars on road daily * Area of city under congestion pricing * Sensitivity to congestion pricing.)

\textbf{Sensitivity to Congestion Price:}

It is the ratio of the number of cars not entering a congestion pricing zone for a particular price to that of the number of cars entering the same congestion pricing zone during a period without congestion pricing. In 2003, when the city of London implemented a congestion pricing scheme in the central area of London, by charging 5 pounds for each car entering the congestion pricing zone during peak hours, the number of cars entering the pricing zone fell from around 196,000 to 125,000. Using this empirical data, a linear demand function of cars and congestion price was obtained. (TFL, 2005).

Congestion Price = y; Cars entering the pricing zone = x;

when y = 0; x = 196,000;
when \( y = 5 \times 1.9 = 9.5 \) (converting pound to dollar); \( x = 125,000 \);

\[
m = \frac{(9.5 - 0)/(125000 - 196000) = 9.5/(-71000) = -1/7473.7;}
\]

hence, \( 7473.7y = -x + 196,000; \) (demand equation)

Using the above equation, sensitivity to congestion price was determined for various prices.

<table>
<thead>
<tr>
<th>Price in Dollars</th>
<th>Cars entering pricing zone</th>
<th>Fraction change in cars entering</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>196000</td>
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Percentage change in population using public transit = \((\text{Average vehicle occupancy} \times \text{Decrease in number of cars on road due to congestion pricing}) / \text{Population}\).

Percentage of population using public transit = \((\text{Initial Percentage population using Public transit} + \text{Percentage change in population using public transit due to pricing.})\)

Actual population using public transit = \((\text{Population} \times \text{Percentage of population using public transit})\)

Percent of population using a car for transportation = \((100 - \text{(Actual population using public transit/population)})\)
Revenue from Congestion Pricing per year = (Cars on road daily*Area under Congestion Pricing * Congestion Price *(1-Sensitivity to congestion Pricing))* Number of Working Days

Revenue recycling policy analysis:

Building more Roads loop:
Most policy makers and drivers view increasing highway capacity as the only means to reduce traffic congestion. Moreover, it is the drivers who pay the congestion price fee; hence their natural demand would be to improve the highway facility. However, statistical data from most of the large cities indicates that in spite of increasing the highway capacity, traffic congestion seems to outpace efforts at enlarging highways. This effect is referred by some traffic analysts as road generated traffic (i.e., the additional vehicle travel that results from road improvement). Since many different factors such as population growth, demographic changes, per capita income and employment affect the VMT, the exact relationship between average miles driven per car and highway capacity is difficult to establish. Hansen showed that the long term elasticity between highway traffic and highways to be 0.9 for California after just 5 years. (Hansen, 1995). Noland’s time series data analysis of various types of roadways indicates that the short run elasticity between VMT and lane mile to be 0.5 and 0.8 in the long run after 2 to 5 years lag. (Noland, 2001). Cervero in his analysis of data on freeway capacity expansion and traffic volume of California estimated the long term elasticity of VMT and highway capacity to be 0.6. (Cervero, 2003). The model described in this paper considers elasticity between average miles driven per car and highway capacity to be 0.6 with a 5 years lag i.e. a 10 percent increase in highway capacity will increase the average miles driven by 6 percent with a lag of five years.

Freeway lane mile added from congestion pricing revenue = (Percentage of road expenditure allocated to freeway * (Percentage revenue allocated to Roads/100) * Revenue from congestion Pricing per year)/(cost of building per freeway lane mile).

Arterial lane mile added from congestion pricing revenue = ((1-Percentage of road expenditure allocated to freeway) * (Percentage revenue allocated to Roads/100) * Revenue from congestion Pricing per year)/cost of building per arterial lane mile.

Cost of building road per lane miles increases at the rate of inflation.

Delay in adding new roads = 4 years.
Percent change in Freeway lane mile = (Freeway Lane Mile - INIT(Freeway Lane Mile)) / INIT(Freeway Lane Mile)

Percent change in Arterial Road lane mile = (Principle Arterial Lane Mile - INIT(Principle Arterial Lane Mile)) / INIT(Principle Arterial Lane Mile)

Road Growth Induced Driving = (Percentage change in freeway lane mile * Elasticity between Road Capacity Growth and per capita driving * INIT(Average miles driven Per car per day)) + (Percentage change in arterial road lane mile * Elasticity between Road Capacity Growth and per capita driving * INIT(Average miles driven Per car per day))

Delay in road growth induced growth = 5 years.

**Lowering Fuel Price Loop:**
In the US, the recent hike in gasoline prices has taken center stage in various political debates across the nation. Hence, a revenue neutral strategy (i.e., by reducing fuel tax with congestion pricing) could make congestion pricing more politically acceptable. Moreover, reducing fuel price would also reduce the total congestion cost since the cost of wasted fuel in congestion would be reduced. However, travel is a derived demand such that reducing the price of travel would invariably increase the amount of travel. Goodwin et al. determined that if the real price of fuel is reduced by 10%, kilometers driven per vehicle increases by 3% in the long-run. (Goodwin et al, 2004) This dynamic change in the driver’s behavior would inevitably increase the congestion cost.

Average fuel consumed (gal.) during peak hour = (Average Daily VMT * Number of working days) / Average Fuel Economy in congestion

Total average fuel consumed = 2 * Average fuel consumed (gal.) during peak hour. (Assuming that 50% of fuel is consumed during peak hour driving.)

Fuel price reduction possible per gal. = (Revenue from congestion Pricing per year * (Percentage revenue allocated to reduce fuel price/100)) / Total average fuel consumed


Percent change in fuel price = (Price of fuel - INIT(Price of fuel)) / INIT(Price of fuel).

Effect of Fuel price reduction on driving = Percentage Change in Fuel Price * Elasticity between price of fuel and driving * INIT(Average miles driven Per car during peak hour).

Annual CO2 emission in tons = Total Average fuel consumed * 8.87/1000
(One gallon of gasoline would emit 8.87 kg of CO2)
**Per Capita Income Driving Loop:**
The fiercest opposition to congestion pricing comes from the social equity point of view. The main thrust of the argument is that those people who have high value for their time, mostly higher income motorists, would be willing to pay and get the full benefits of the scheme whereas low income motorists may be forced to travel outside peak hours or may be forced to change to other modes of transportation which could be highly inconvenient. One way to address this potential inequality is to redistribute the revenue generated from congestion pricing to low income drivers in the form of tax breaks. The net effect of this measure is that it would increase the average per capita income of the people in the affected region. Goodwin et al estimated that if the real income rises by 10% then vehicle km per vehicle would increase by 1.7% in the long run. (Goodwin et al, 2004)

\[
\text{Per capita additional income given from congestion pricing} = \frac{(\text{Percentage revenue allocated to income}/100) \times \text{Revenue from congestion Pricing per year}}{\text{Population}}
\]

\[
\text{Annual average per capita income} = \text{Normal Average per capita income} + \text{Per capita additional income given from congestion price revenue}.
\]

Normal Average per capita income grows with the economic activity in the region.

\[
\text{Percent change in income} = \frac{(\text{Annual average per capita income}) - \text{INIT(Annual average per capita income)}}{\text{INIT(Annual average per capita income)}}
\]

\[
\text{Effect of increasing income on driving} = \text{Percentage change in income} \times \text{elasticity between average income and driving} \times \text{INIT (Average miles driven Per car during peak hour)}
\]

**Increasing public transit expenditure loop:**
Many transportation experts attribute rising congestion to increasing private vehicle use and deteriorating public transit service. Small suggests that congestion pricing would give rise to a “virtuous circle’ in which congestion charges first would increase the ridership of public transit due to mode shift which in turn improves the speed, service and operating budget of the public transit agency. Improvement in operating budget could lead to reduced fare and increased service which would again increase the ridership. This increase in ridership would give rise to another round of improvements. This reinforcing loop would stop when the system reaches equilibrium (Small, 2004). However, almost all public transit services in the world are highly subsidized by the government and ticket fares do not cover the full operating cost. (WBCSD, 2001). Moreover, expansion of public transit service is highly capital intensive and revenue from increased transit ridership would be inadequate to expand transit service to a very great extent. Hence, the probability of improvement and expansion of public transit service through increased ridership due to congestion pricing is quite low. The major improvement in public transit service could only be possible when the revenue from congestion pricing is used for improving transit service. Elasticity between transit service and ridership depends on various parameters such as the initial share of travelers held by the public transit system, population density and accessibility. The model discussed in this paper assumes an elasticity of 1 during the first six years and then the elasticity gradually reduces to 0.5 at the end of twenty years. The reason for using high
elasticity for the first six years is that markets with the highest initial public transit use potential would be served immediately and this would result in a large ridership gain during the initial periods.

Revenue allocated to public transit = \((\text{Percentage of revenue allocated in public transit service/100}) \times \text{Revenue from congestion Pricing per year}\)

Expenditure of public transit service = Initial expenditure of public transit system + Revenue allocated to public transit.

Percent change in public transit expenditure = \((\text{Expenditure of public transit service-Initial expenditure of public transit system}) / \text{Initial expenditure of public transit system}\).

It is assumed that the level of public transit service is directly proportional to the expenditure on public transit service.

Percent change in public transit ridership due to improved service = Elasticity between public transit service and ridership * Percentage change in expenditure of public transit * INIT(percentage population using bus).

Model Results:
The following simulation was conducted using the model:

1) Base case – No Congestion Pricing:

When a No Congestion Pricing scheme is implemented, the number of cars on the road continues to rise at the same rate as that of population growth. The annual total congestion costs however, rises at a much higher rate than that of the population growth rate. This is due to the fact that when a new car is added on the road it adds to the delay of all the vehicles that are already present on the road. As can been seen from the Figure 5 below, the annual total congestion cost and the annual vehicular CO2 emissions rises at a rate of approximately 10% annually when no congestion pricing is implemented. If cities do not implement any congestion mitigation strategy then the cost of congestion will be quite substantial in the future.
2) Congestion Pricing Scheme Implementation without revenue recycling:

At $t=1$ years, ten percent of the city is brought under the area wide congestion pricing scheme and the congestion fees of $5.00$ is charged for every car on the road in the congestion pricing zone. Both area under congestion pricing and price are kept constant. As can be seen from Figure 6 and 7, just introducing congestion pricing without any revenue recycling reduces the annual total congestion cost and annual CO2 emissions initially. However, when the new equilibrium between public and private transit mode share is reached, then the total cost of congestion rises at almost the same rate as that of the situation under the no Congestion Pricing scheme.

Figure 6: Total congestion cost with congestion pricing scheme without revenue recycling.
3) Congestion pricing scheme with revenue recycling policies:

Government’s revenue recycling policies are one of the most important factors which would determine the political acceptability of a congestion pricing scheme. At \( t=1 \) years, ten percent of the city is brought under the area wide congestion pricing scheme and the congestion fee of $5.00 is charged for every car on the road in the congestion pricing zone. Both area under congestion pricing and price are kept constant. Five different policy options are considered in the model for revenue recycling. They are: 1) spending on public transit service 2) giving tax rebates 3) reducing gas price 4) increasing highway capacity and 5) allocating equally among all the four previous options.

1- Congestion pricing without revenue recycling; 2- Revenue allocated to public transit system;
3- Revenue allocated to reduce tax; 4- Revenue allocated to reduce fuel price; 5- Revenue allocated to increase highway capacity; 6- Revenue equally allocated to all for options

Figure 7: Annual CO2 emissions with congestion pricing scheme without revenue recycling

Figure 8: Total congestion cost with congestion pricing and revenue recycling;
As can be seen from Figure 8 and 9, when congestion price revenue is allocated to reduce tax and fuel price there is no significant difference in the annual total congestion cost and CO2 emissions with respect to a congestion pricing scheme without a recycling option. The main reason for this trend is that the percentage change in the pre capita income due to revenue reallocation through taxes is quite low hence its effect on annual total congestion cost is very negligible. In the case of reducing fuel price by reducing fuel tax, there is a reduction of fuel price which would reduce annual total congestion cost. However, this reduction is offset by increase in average miles driven per vehicle which in turn increases the congestion cost hence the effect of reducing fuel price on annual total congestion cost is also negligible. As can be seen, allocating congestion pricing revenue to increase public transit system lowers the annual total congestion cost and CO2 emissions significantly during the initial periods because of the mode shift between the private vehicles and public transit. However, as soon as the equilibrium in ridership is reached the annual total congestion cost and CO2 emissions begins to rise at almost the same rate as of Congestion Pricing arrangement with no revenue recycling options. On the other hand, increasing highway capacity does not lower the congestion cost significantly during the initial period but this policy significantly lowers the annual growth rate of congestion cost such that after a period of 19 years congestion cost with this policy option is almost same as the policy option of allocating congestion pricing revenue to public transit. However, from Figure 9, it can be inferred that the CO2 emission under this policy option is very much greater than the CO2 emission resulting from policy option of allocating congestion price revenue entirely to the public transit system. Allocating revenue equally to all the four policy options lowers the congestion cost as compared to allocating solely to reduce tax and fuel price, but congestion is much higher when compared to the option of allocating to the public transit system only.
4) Congestion pricing scheme with revenue recycling and periodic congestion price increment:

In this simulation, at $t = 1$ years, ten percent of the city is brought under the area wide congestion pricing scheme and the congestion fee of $3.00 is charged for every car on the road in the congestion pricing zone. After every three years congestion price is increased by $2.00. Since, the policy option of allocating revenue to reduce tax and fuel price does not have any major effect on the congestion cost, this option is not considered in this simulation.

1- Congestion pricing with no revenue recycling; 2- Revenue allocated to public transit system
3- Revenue allocated to increase highway capacity;

![Figure 10: Total congestion cost with congestion pricing scheme with revenue recycling and periodic congestion price increment.](image)

![Figure 11: Annual CO2 emission with congestion pricing scheme with revenue recycling and periodic congestion price increment.](image)

As can be seen from Figure 10, the congestion cost for the policy option of increasing highway...
seems to increase initially for a few years at a rapid rate but the rate of increase declines sharply after 6 years. The reason for the rise in congestion cost for this option in the initial few years is that there is a delay of 4 years in constructing new roads or in increasing highway capacity. On the other hand, for the policy option of increasing public transit services, the annual congestion cost does not increase for approximately the first thirteen years. After the thirteenth year congestion cost gradually begins to rise exponentially, and after the nineteenth year the congestion cost of the policy option of increasing public transit service is almost same as the policy option of building more roads. However, as can be seen from figure 11, CO2 emission from the policy option of increasing highway capacity is much greater than the policy option of allocating congestion price revenue to public transit service.

5) Congestion pricing with revenue recycling with periodic increment in congestion price area

In this simulation, at t=1 years, five percent of the city is brought under the area wide congestion pricing scheme and the congestion fee of $5.00 is charged for every car on the road in the congestion pricing zone. After every four years are under the congestion pricing scheme is increased by 5 percentage point. Since, the policy option of allocating revenue to reduce tax and fuel price does not have any major effect on the congestion cost, this option is not considered in this simulation.

1- Congestion pricing with no revenue recycling; 2- Revenue allocated to public transit system
3- Revenue allocated to increase highway capacity;

Figure 12: Total congestion cost with congestion pricing scheme with revenue recycling and periodic increment in congestion price zone area
As can be seen from Figure 12, similar to previous simulation run the congestion cost for the policy option of increasing highway capacity seems to increase initially for a few years at a rapid rate but the rate of increase declines sharply after 6 years. On the other hand, for the policy option of increasing public transit system services, the annual congestion cost does not increase for approximately the first thirteen years. After the thirteenth year congestion cost gradually begins to rise exponentially, but unlike the last simulation the congestion cost resulting from the policy option of increasing highway capacity is quite high than the option of improving public transit system. Similar to the previous simulation, CO2 emission from the policy option of increasing highway capacity is much greater than the policy option of allocating congestion price revenue to public transit system.

6) Congestion pricing scheme with revenue recycling, periodic congestion price and area under pricing increments:

In this simulation, at $t=1$ year, five percent of the city is brought under the area wide congestion pricing scheme and the congestion fee of $3.00$ is charged for every car on the road in the congestion pricing zone. After every three years the congestion price is increased by $2.00$ and after every five years the area under congestion pricing is increased by five percentage points. Since, the policy option of allocating revenue to reduce tax and fuel price does not have any major effect on the congestion cost, this policy option is not considered in this simulation.
1- Congestion pricing with no revenue recycling; 2- Revenue allocated to public transit system
3- Revenue allocated to increase highway capacity

As can be seen from Figure 14, without any revenue recycling, congestion cost rises over the period of time, but at a much slower rate than the previous simulation. Building more roads or increasing highway capacity initially does not reduce congestion for some years. After few years, the growth in congestion cost with this policy option saturates but CO2 emissions continue to rise in this case. However, on the other hand the policy of allocating revenue to public transit system greatly reduces the congestion cost and CO2 emission in the initial period. Though, congestion cost and CO2 emission starts to increase after two decades the rate of increase is very much low under this policy option.
Conclusions:

The following conclusions could be drawn from this analysis:

First, implementing a congestion pricing scheme without any revenue recycling policy will not reduce congestion cost in the long run. It might reduce congestion for a brief period and increase public transit ridership. However, when the equilibrium in ridership is reached then, congestion would begin to rise again. Hence, implementing congestion pricing without any revenue recycling policy will just create a delay in the congestion before reaching certain levels without congestion pricing.

Second, the policy option of reducing general tax and fuel tax does not reduce congestion cost significantly as compared to a Congestion Pricing scheme with no revenue recycling option. Moreover in the long run reducing fuel price could be counter productive as people may opt for bigger and less fuel-efficient vehicles which would increase the overall fuel consumption. Increase in fuel consumption would lead to an increase in CO2 and other pollutants emission, increase the congestion cost as the average fuel economy of vehicle fleets would be low which would cause more fuel to be wasted under congested conditions.

Third, from this model it may be concluded that building roads or increasing highway capacity from congestion price revenue would reduce the rate of increase of congestion cost in the long run. However, form the simulation run on this model, it has been observed that the CO2 emissions reduced from this policy option is quite marginal than compared to no revenue recycling option. The main reason for this trend is that by building roads or by increasing highway capacity the average speed of the vehicle on road is increased hence the time spent on road is reduced but building more roads increases more miles driven per vehicle which increases the fuel consumption and hence increase CO2 emission. Also, this option has many undesirable effects such as building more roads may increase suburban sprawl and lead to decentralization of city and reduce population density. This would inevitably reduce the effectiveness of public transit service and make people more dependent on private vehicles for mobility needs. Moreover, the model assumes the real price of fuel to be constant. If the price of fuel increases in the future, then future households may have to spend a larger share of their income on transportation which would reduce their disposable income and could stifle economic growth.

Fourth, effectiveness of congestion pricing is greatest when the revenue from congestion pricing is used to improve public transit service. Improvements in public transportation service would increase ridership which would reduce congestion cost. However, the probability of creating a “virtuous circle” or an reinforcing loop (increase in service would increase ridership which would increase the revenue and would again increase service.) is quite low since almost all public transit service systems in the world do not recover their entire operating cost from ticket fare. Hence a periodic increase in the congestion price and area under the congestion price is the best option to reduce the congestion cost in the long run provided the revenue from congestion price is allocated to improve public transit service. Hence, the strategy employed by the City of London to reduce congestion could be quite successful in reducing annual total congestion costs in the long run.

The model described in this paper is a simplified model of urban peak hour traffic congestion which only considers two modes – public transit and private vehicles. In reality there are other modes such as
cycling, walking and taxis which are not considered in this model. Also, the change in average vehicle occupancy and the use of alternate path by those drivers affected by congestion pricing should be examined. The model assumes that the road network and population density are uniformly distributed within the city, but in general population density is much higher in the center of the city than its outer fringes. Also, the effect of congestion pricing on the number of business transaction within the pricing zone is not simulated in this model. It would be quite beneficial to examine these issues in an expanded model.

Climate change is one of the biggest threats the humanity is going to face in the 21st century. Transportation sector is one of the biggest emitter of green house gas - CO2 which is responsible for climate change. The most publicly debated options for reducing CO2 emissions in transportation are increasing the fuel economy of vehicles and bio fuels i.e. bio ethanol. However, these options have many drawbacks. First, increasing the fuel economy of vehicles would reduce the cost of driving per mile but it would also increase the average miles driven per car which would reduce the effectiveness of this option. Moreover replacing entire stock of vehicle fleets with a more fuel efficient fleet would take a long time and is quite expensive. The recent high gasoline price has ignited the public debate on bio fuels as the best alternative to fossil fuel which would reduce CO2 emission, however many scientists agree that the existing procedure of producing bio ethanol from corn, is not an appropriate one and some studies even revels that the existing system of producing bio ethanol consumes more energy than they produce which completely eliminates their ability to reduce CO2 emission, (Pimentel et al, 2005). As can be seen from the simulations, an area wide congestion pricing scheme with appropriate revenue recycling option has a great potential to reduce CO2 emissions from automobiles in large cities and henceforth, it should be considered among other policy options to mitigate climate change.
Reference:


Robert Cervero, “Are Induced Travel Studies Inducing Bad Investments?,” ACCESS, Number 22, University of California Transportation Center, Spring 2003a, 22-27.


Appendix I:

Sensitivity Analysis:

In this section we examine the effect of change in congestion cost with no congestion pricing scheme and with area wide congestion pricing scheme with periodic increment in congestion price and zone area. Also, the revenue from congestion pricing is equally allocated to increasing highway capacity and public transit service, when Key Model variable assumption are varied.

The most important key variable in the assumption are:

1. Initial Population
2. Population Growth Rate
3. Initial Market share of public transit system

Initial Population:
In this simulation run, the initial population was varied + or – 15 percent from the base condition and all other model parameters we maintained constant.

Fig: I with no congestion pricing.

Population:
1 8,500,000
2 10,000,000
3 11,500,000
Population Growth Rate:
In this analysis, three population growth rate scenarios were considered. In scenario 1, initial growth rate of 2.6 percent annually was assumed and the growth rate was gradually declined to 1.4 percent per annum. In scenario 2, a constant population growth rate of 1.5 percent was assumed. And in scenario 3, initial growth rate was assumed to be 1.3 percent and was gradually declined to .8 percent.

1) High population growth rate 2) Constant growth rate 3) Low growth rate
Initial Market share of public transit system:
In this simulation three different initial market share of public transit system was assumed which are 1) 25%  2) 15% and 3) 5%.

Future fuel price:
In this simulation three different fuel price – low, modest and high increase future prices was assumed. In the low price scenario, fuel price increases gradually from $3 per gallon to $4 per gallon in 20 years. In the modest price scenario, fuel price increases gradually from $3 per gallon to $6 per gallon in twenty years and in high price scenario, fuel price increase from $3 per gallon to $8 per gallon in twenty years.
Fig: VII with no congestion pricing.

Fig: VIII with congestion pricing.
Integrated Frameworks for New Mobility: From Northern Rural Landscapes to International City Regions

Summary by Lisa Aultman-Hall, August 2008

Introduction

In the spring of 2007, an interdisciplinary team of researchers from the Universities of Vermont, Michigan and Illinois, conducted a series of sessions to consider applying the concepts of new mobility Hubs beyond the urban context. This team included authors of a large research grant proposal to the University of Vermont Transportation research Center: Lisa Aultman-Hall, Susan Zielinski, Robert Costanza, Peter Dodds, Thomas Gladwin, Donna Rizzo, Irving Salmeen, and Moira Zellner.

The inclusive complex systems-based framework was envisioned as a portfolio of modeling options to support effective New Mobility hub network analysis and solution building that includes seamless multimodalism (including in the form of New Mobility hub networks), as well as accessibility by proximity and technology. This framework, and the accompanying decision tool matrix was envisioned to apply to all landscapes from rural through large city region, including retrofitting suburbs. Furthermore, the performance metrics used to evaluate effectiveness were identified as being useful in all environments and include both movement and non-movement based factors including quality of life. The planned matrix of modeling tools for assessment and implementation of New Mobility hubs needs to include the advantages and disadvantages of the range of modeling approaches that support seamless New Mobility, as well as the associated data needs. Pilot studies in different context were suggested as the means to accomplish development of these matrices.

Background

There are increasing indications that American-style automobile- and highway-based transportation systems are failing. While freeways are being built at unprecedented rates in China, the very rural state of Vermont is pursuing a statewide no-build transportation policy entitled “the road to affordability” in recognition of our society’s inability to financially maintain the system we have. At the same time, the Federal Highway Administration (FHWA) has prioritized congestion mitigation as a research and operational high priority area (USDOT 2003 and 2005).

Our communities are realizing that our personal transportation system is creating more than just smog and air toxics, it is also a major contributor to global climate change. And while many have enjoyed the positive aspects of a pervasive automobile culture, many have not. In America, public transit systems struggle for both capital and operational funding and our land use patterns preclude walking and biking in all but a handful of urban areas. A small percentage of the global population is using a disproportionate share of transportation energy. In short, the global transportation system fails to be sustainable with respect to environment, social justice and economics.

At this turning point in transportation history, innovative, integrated transportation solutions developed within a global framework are essential to providing widespread sustainable human wellbeing. Models and frameworks that unintentionally perpetuate
the current highway-based transportation system must be abandoned. Unfortunately to
date, the application of fully integrated mobility models are very limited and most often
focus on large urban areas. Although innovative solutions are increasingly plentiful in
response to the global transport and quality of life needs mentioned above, they have
seldom been applied together in a user-friendly suite that actually promotes uptake, and
therefore sustainability.

In recent years, the concept of “New Mobility” has become a transformative force in
urban transportation (Zielinski 2006). New Mobility is about moving people, moving
goods, and moving less, in ways that are cleaner, greener, safer, healthier, more
equitable, customized, and connected. New Mobility even addresses the fact that you
might not need to travel at all (or significantly) to fulfill your needs; that is, the
connections between people, services and activities can also be made through
telecommunications including the internet and by land use and urban design that brings
amenities and activities closer together.

Moving Beyond the Urban Context

This Spring 2007 discussions of the interdisciplinary group were based on the
importance of connectivity and the desire to have methods and goals that apply across
all space human occupy – both rural and urban. More often than not individual solutions
are evaluated or even built and have often failed because the complementary system
components were not in place. We suggest that rural and urban landscapes and their
interdependence (food systems or forests for example) are part of one system.
Moreover, we argue that the measures currently used to evaluate individual system
components such as vehicle miles traveled or energy consumed are not sufficient, or
even appropriate for designing an overall optimal system. Furthermore, we believe that
current techniques and system boundaries skew modeling results and often point to non-
optimal policy directions because they focus on only a single aspect of a complex and
interdependent transportation system. For example if one evaluates a full size transit bus
with one passenger based on emission per passenger mile, the bus is not worthwhile.
Alternatively, if one evaluates a car sharing enterprise alone for CO2 savings and
congestion alleviation, the benefits are relatively marginal. Within the larger multi-modal,
integrated system however, an effective car sharing enterprise can provide the missing
link to ensure system efficiency and sustainable transportation uptake.

Our research discussions were underpinned by the premise that to build and apply a
framework for understanding and applying integrated New Mobility as a whole system it
must work in all types of geography. This holistic framework will include modeling
approaches and associated data and approaches that address all components of the
system. For example, current transportation models consider physical networks
relatively well with exogenous demand inputs, but fail to consider the management and
business strategies within the system, nor do they consider cultural motivations and
aspirations. Whatsmore, while state of the art models incorporate human activities as
input (Lee et al. 2002 and Doherty 1998), most transportation models in practice fail to
incorporate travel as a derived demand. When analysts consider only individual
components of the system, for example highway traffic (which is easiest to model and
has the most readily available data), solutions that would utilize biking and walking are
unintentionally excluded from the optimal output. Ultimately, we compromise the true
range of policy and implementation options available when we follow the engineering
tradition to simplify a system and analyze only individual components. New Mobility hub
networks and complex systems modeling frameworks demand integrated multi-faceted analysis and provide a construct for including a range of components in a system.

Most importantly, we hypothesize that integrated New Mobility modeling and implementation approaches are applicable in all environments, from rural northern landscapes to international city regions. This is not to suggest that the optimal components for sustainable transportation systems are the same for all environments, but rather that true measures of mobility and accessibility, and a suite of modeling tools and implementation approaches, should be amenable to use everywhere.

The group believed that framework for integrated, multi-faceted transportation solutions and innovative New Mobility hub networks can be developed for all areas including smaller urban areas and rural locations. Indeed, the congestion motivation for New Mobility is rapidly being replaced in all urban, suburban and rural locations by an increasing need to address the relationship between transportation and 1) energy; 2) environment; 3) public health; 4) personal and public finance; 5) an aging population with complex needs; 6) integration with information technology; and 7) the critical link to quality of life and environmental justice. All of these factors drive the need to develop a framework for New Mobility hub networks that will also be useful in regions of the world where urban densities and congestion do not exist per se. There is a need to know which modeling tools are best suited for different environments as well as what data and frameworks are needed to apply the models for both assessment and implementation.

Most existing examples of New Mobility and New Mobility hub networks are within large city regions such as Toronto, London, Copenhagen or Paris, but other examples come from less densely populated regions of the world (Bremen, Germany for example). To date most of the efforts to apply modelling techniques for assessment and design of mobility hub networks have focused on the urban context.

Within urban systems, leading edge researchers are beginning to apply integrated modeling approaches. One example is the effort at the University of Toronto (Miller and Silvini 2005; Miller and Roorda 2006; Roorda et al. 2006). This group integrates land-use activities and transportation aimed at measuring environmental impacts. It is important to note that these efforts integrate many aspects of the overall system using new variables that are not typically included in traditional transportation engineering or planning models. We suggest going even further to include measures used in ecological economics to consider overall human well-being (Costanza et al. 2007). Others (Sussman and Hall 2004 for example) have, as we do here, advocated the use of complexity approaches (Miller and Page 2007, Boccara 2004) to address overall sustainability in transportation systems.

The University of Vermont Transportation Research Center’s theme is sustainable systems and advanced technologies for northern communities. The objective to advance the New Mobility hub network concept in the complete range of environment types within the global community stems from this theme. Current effort involves the UVM teams partnering with research groups that have mobility research experience in the urban and international context who seek to generalize this framework to include a full range of environment types. This extension allows in addition to the rural landscape, the weather and the northern climate to also be considered as these factors affect the type of mobility hub network that will succeed in a given location.
In summary, both global and local communities need New Mobility modeling frameworks that:

- Consider all types of system components at one time (physical, organizational and social);
- Measure efficiency in holistic sustainability or human-based quality of life terms; and
- Can be applied in all environments globally.

It is deemed reasonable to develop and apply an inclusive complex systems-based framework that presents a portfolio of modeling options to support effective New Mobility hub network analysis and solution building that includes seamless multimodalism (including in the form of New Mobility hub networks), as well as accessibility by proximity and technology.

References


http://www.nae.edu/nae/bridgecom.nsf/weblinks/MKEZ-6WHPJK.
MOTIVATING THE ADOPTION OF SUSTAINABLE TRANSPORTATION

AVIK BASU

Industry often models consumers as rational beings who make choices to maximize their gain. A simple example of this would be commuters giving up driving their personal automobile in favor of taking public transit based on the relative cost of gasoline versus the cost of riding the bus. In the other extreme, some environmentalists urge consumers to put aside the issue of gain and make sacrifices in order to live more sustainably. In this case, consumers choose to ride the bus because it is better for the environment. While both strategies may work in the short-term for some people, both oversimplify human motivations to the issue of gain. In reality, people are motivated by multiple concerns (Midgley, 1978) and therefore it is necessary to approach the issue taking into account self-interest, concern for the environment, the desire for a better life, and other factors. Addressing this issue, Kaplan (2000) calls for strategies which are "multiply desirable". Such strategies would meet a variety of needs simultaneously and thus would improve the overall experience and the ultimate success of new transportation paradigms. Two specific areas of needs are presented here.

THE NEW MOBILITY SHOULD NOT REQUIRE A SACRIFICE; IT SHOULD INSTEAD ENHANCE QUALITY OF LIFE

The popularity of the automobile in this and other countries is due in large part to the perceived quality-of-life enhancements—convenience, social status, safety, comfort, health, and others—it affords over other transportation modes. In the long run, people cannot be expected to sacrifice their quality of life in order to behave more sustainably. The New Mobility must therefore provide an overall advantage over the personal automobile. In some ways, the SMART project is studying ways to do just this. For example, to improve convenience, the project researches transportation networks to improve accessibility. While accessibility is an important issue, the design of the built environment is also pivotal in promoting adoption.

VEHICLE DESIGN

The design of transportation vehicles has potential to influence ridership. A recent study—amusingly subtitled Please don’t make me sit in the middle—considers the effects of crowding on stress levels in New York City trains (Evans & Wener, 2007). The researchers found that while proximity to other passengers increases stress, the overall density of passengers had no significant effect. Based on these findings, the authors recommend larger seats, avoiding middle seats, and providing for a prop (armrest, table, etc.) to preserve one’s personal space. Since the density of the car is not significant, larger cars can be built to offset the cost of fewer seats per car. Research such as this gives us guidelines for designing transportation infrastructure in a way that could improve adoption rates and improve the overall experience of mass transit. Further research could catalog existing vehicular designs to study how each influences:

- A sense of safety
• Productivity
• Noise levels
• Crowding
• Mental fatigue (S. Kaplan & Kaplan, 2003)
• Culturally-sensitive notions of social status

LAND-USE DESIGN

According to the Department of Transportation’s Bureau of Transportation Statistics, there are 250 million registered passenger vehicles in the U.S., representing more than one vehicle for every person over the legal driving age. Researchers have linked land-use designs (where and how to place homes, offices, stores, roads) to increased personal automobile use (Burchell, 2002; Ewing, 1997) as well as decreased non-motorized transport (Sallis, Frank, Saelens, & Kraft, 2004). However, just as current patterns of development have promoted the automobile, alternative land-use designs can facilitate alternative transportation modes. For example, Frank et al. have pointed out that the design of street networks in a grid fashion can facilitate walking through increased connectivity (i.e. shorter walkable distances) between destinations (Frank, Engelke, & Schmid, 2003). The same authors who did the stress study on commuter trains (described in the previous section) have also found that the length of commute times increases stress levels, thus implying a need for proximity between home and work (Evans & Wener, 2006). On the same topic, Cervero and Duncan asked which land-use strategy would be better: to bring either jobs or retail/consumer services closer to residential areas. They found that land patterns which bring work and home closer together are substantially more effective at reducing travel (Cervero & Duncan, 2006), thus giving planners an area in which to focus their efforts.

With obesity rates in the U.S. now at epidemic proportions—according to the National Health and Nutrition Examination Survey, nearly 1 out of 3 adults are obese—it is not difficult to make an argument for walking or biking based on health reasons. Several studies have now considered the relationship between land-use patterns and obesity, and have found some evidence that residents of “compact” cities—ones with higher density and mixed land uses—are more likely to walk, spend less time in automobiles, and are less likely to be overweight and obese (Ewing, Schmid, Killingsworth, Zlot, & Raudenbush, 2003; Frank et al., 2006). Other researchers (Swanbrow, 2008; Tilt, Unfried, & Roca, 2007) have looked at the effects of different landscape designs on non-motorized transport and found that an area’s greenness can improve walking rates and provide associated health benefits.

It is clear that land-use patterns have the potential to play a major role in the success of alternative transportation modes. The studies mentioned here come from a wide range of disciplines including planning, public health, landscape architecture, and environmental psychology. What remains necessary is the compilation of information from these disparate sources and development of a catalog of various types of land-use designs and their impact on quality-of-life related issues. Applying these theoretical results to transportation design could help motivate more sustainable behavior by the public.

THE NEW MOBILITY MUST SUPPORT HUMAN INFORMATIONAL NEEDS

Getting people out of their cars may be one of the more challenging tasks of the sustainable transportation initiative. This second, more subtle, set of needs has to do with the role information plays in getting people to make such difficult choices. Humans are strongly, and sometimes strangely, motivated by information. We want to know about things. We enjoy feeling competent about our knowledge, but we get bored with the same old things. We crave new information and are motivated to explore beyond our know-how, but new information can
confuse us and we abhor being confused so we retreat to our competencies. A relatively new behavioral model called the “Reasonable Person Model” (RPM) posits that people will behave more reasonably when their environment supports understanding, exploration of new ideas, and opportunities for meaningful action (R. Kaplan & Kaplan, 2006; S. Kaplan & Kaplan, 2003). This section applies this model to the present context.

PROMOTING UNDERSTANDING AND EXPLORATION

An effective way to influence people to avoid alternative transportation modes is to undermine their ability to make sense of them and learn more about them. One approach to improving the comprehension of transit systems is to provide transit information in a user-friendly manner. Google Transit Maps (http://www.google.com/transit) freely provides point-to-point directions, time estimates, and cost information for public transit in many cities around the world. Its basic interface is easily and globally accessible via internet-enabled computers and mobile devices. Google also provides users the option to choose between driving and public transit, which allows people to virtually explore their transportation options and build a more vivid familiarity with the system without ever having used it. Such internet-based tools have great potential to help people develop a practical knowledge of alternative transport; however it should be noted that excessive quantity or complexity of information can easily lead to confusion, which will likely result in a retreat to the familiar (i.e. driving).

Maps and directions are effective ways to promote understanding. A more direct approach is to structure transportation networks themselves in a way that supports users’ understanding and wayfinding abilities. For example, the more transfers required between two destinations in a public transit system increases not only the travel time, but also the complexity of the travel. This could explain why researchers have found more transfers to increase stress levels (Wener, 2003). Developing networks that require fewer transfers could make it less daunting for would-be riders. In residential neighborhoods, the design of street networks can impact wayfinding. Grid pattern street designs are easier to navigate than cul de sacs and thus promote not only wayfinding, but increased walking rates as well. In his classic Image of the City, Lynch (1960) showed how the structure of some cities helps people build mental models, while the structure of others undermines it. The SMART project is affiliated with several cities spread around the world (Bangalore, Cape Town, and Detroit) each with innovative transportation plans. These systems can be compared for how well they help people build an “image” of the transportation network. These approaches can then be used in other systems to enhance understanding and exploration.

TRYING THINGS OUT

Another approach to encouraging exploration is to make it easier for people to try out alternative transport modes. The League of American Bicyclists promotes an annual Bike-to-Work week which raises consciousness about the benefits of bicycle commuting and also gives people some social support to try it out. A recent study showed the effectiveness of a one-month free travel card in freeing people of their habit of using their cars and turning them on to mass transit (Thøgersen & Møller, 2008). Land-use designs which place transit stops near people’s homes may offer a better chance of trying it out. Giving people the opportunity to experiment in this way is essential to the adoption of new alternatives. In Diffusion of Innovations, Rogers (1983) lists trialability as a main factor in improving adoption rates of new cultural ideas. Irvine and Kaplan (2001) agree that people are more likely to accept change when given the ability to try things out, but they emphasize the importance of doing so on a small scale while retaining some familiar elements. Alternative transportation must therefore not provide a drastic change from existing modes, but rather a more gradual shift which, through incentives and design, encourages new riders to give it a try.
MEANINGFUL ACTION

Finally, it is not enough that people are able to make sense of and try out new transportation modes. They must also have the opportunity to use their knowledge in a meaningful way. Involving local people in the planning process is one approach that is essential to the success of sustainable transportation. Locals have an intimate knowledge of their communities that is very different from perspective of those working at a large scale (such as academics and planners). They may have a better sense of when, how, and by whom transportation systems will be used. They could say whether there should be more mass transit or more sidewalks. They likely know the idiosyncrasies of their community to which planners may be oblivious. They will not feel the need to make their ideas generalizable to communities on the other side of the world. The Local Council of Governments provides five reasons to support participatory planning (available at http://www.lgc.org/people/public.html):

• To insure that good plans remain intact over time. ...A plan which involves the public in its creation will have a long-lasting and stable constituency.

• To reduce the likelihood of contentious battles before councils and planning commissions.... A proactive planning process which includes a well-designed public involvement component allows residents to understand exactly what it is they are getting and assures that most people will be happy with the plan and the individual projects at build-out.

• To speed the development process and reduce the cost of good projects. Projects, which are well-designed but have not included public involvement may face opposition which will slow or stop the project....

• To increase the quality of planning. Professionals are not the only ones generating good ideas...

• To enhance the general sense of community and trust in government...

Some common ways of promoting participation are public meetings, workshops, and interviews with stakeholders. In addition to these, there are two other promising ways to better involve the public. The first is known as Public Participation Geographic Information Systems (PPGIS). These systems take advantage of the wealth of spatial data that is now available for most parts of the world and packages it for use in a virtual public meeting. Users can view maps of their communities, comment on important features, and make recommendations with a better sense of their impacts on the larger community. Such systems have the potential to be catalysts for participation in a transportation planning context (Tang & Waters, 2005).

The second approach, visual preference research (R. Kaplan & Kaplan, 1989), is far less technical but carries a better-proven track record (perhaps because of its relative simplicity). It has been shown to be a useful tool for gauging public opinions about the design of places. In this method, participants are asked to rate a set of images depicting development alternatives. The use of images effectively engages the public. As opposed to open-ended questions like “what do you want?”, the presentation of alternatives gives some structure for participants to meaningfully respond. Though it has been used in the past for general land planning issues, it could readily be adapted to transportation-specific issues. Urban Advantage (http://www.urban-advantage.com) provides some vivid imagery of what the alternatives may look like.

Since many decisions, like placement and design of neighborhood roads, transit stops/routes, bike paths, and walking trails, are approved by local citizens, ignoring their input could have costly consequences. Instead, utilizing the knowledge and skills of these civic-minded people will not only help create a system that is suited for the local
community, but will also provide an opportunity for locals to be involved in the design process, make a meaningful contribution, and take ownership of the outcome. Furthermore, it could help counter what Kaplan (2000) describes as the “pervasive malaise of helplessness” that is now associated with environmental problems. These in turn could help promote the adoption of a sustainable transportation system that is ultimately cooperatively designed.

## CONCLUSION: A HUMAN-NEEDS APPROACH TO SUSTAINABLE TRANSPORTATION RESEARCH

Based on the issues mentioned here, the following research themes could integrate with the existing SMART/CARRS proposal and promote a better understanding of human factors in the transportation context:

- Apply research on human needs and motivations in analysis and simulation models
- Synthesize data from disparate sources to develop a sharable catalog of vehicle and land-use plans which would enhance quality of life, support human needs, and promote adoption of sustainable transportation
- Use RPM as a starting point to better understand the role information can play in helping people make more sustainable decisions
- Use participatory approaches to understand how human factors in transportation vary around the world

Realizing the dream of sustainable transportation will require not only infrastructure to move people and goods, but must also undertake “the complex task of moving hearts and minds“ (Zielinski, 2006). Assuming a Field of Dreams mentality, where hoping that development of infrastructure will result in its adoption over competing transportation modes, is a risky endeavor since the competition could be cheaper, faster, more comfortable, and more familiar. Ensuring that sustainable modes of transport are adopted by the public will require an understanding of the public’s motivations and needs and a concerted effort to ensure those multiple needs are met. Success will require a cultural shift about transportation, reframing the currently-perceived sacrifice of giving up one’s car as a choice that enhances one’s quality of life.

## REFERENCES


Priority Research Directions in New Mobility: 2008 – 2012

Recommendations to the University of Michigan's SMART project

29 July 2008

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New mobility Program Recommendations P 2008 - 2012

1. **Exploring the IT/Logistics interface between travelers and service providers**

   This is probably the hottest, richest single opportunity area for both industry and the mobility sector in all its many parts. And it’s our guess that the most tangible interface of this new and much needed relationship between supply and demand will be the mobile telephone. The possibilities are huge, wild and will richly reward those who get their first. *(Our program reference: Reinventing Transport in Cities at http://invent.newmobility.org)*

2. **Transition strategies for car owner/drivers**

   - as cities convert to non-car based mobility systems

   One of these is clearly carsharing, but there are many other opportunities areas there as well. One example among many: information systems and reservation arrangements for parking as drivers come into the city. *(See our attached NewDrive” note which while rough does set out some of this in a bit more detail.)* *(Our program reference: NewDrive at http://www.newdrive.newmobility.org)*

3. **Dynamic billing and control strategies for moving vehicles**

   This is a large super-set which extends through the many variants of road pricing, including congestion charging, tolling, etc. – and combines the innovative use of economic instruments with state of the art IT applications.

4. **TPS – Transport priority systems**

   One of the keys to the huge improvements that are both possible and much needed in our transportation arrangements in cities has to do with the rationalization of the existing built infrastructure to make more space available to vehicles that have the right fit with our 21st century realities and priorities: low carbon, resource efficient, space-efficient and far more varied mobility options. If this approach is to stick it cannot offer just minor improvements to only specific target groups, but must be seen as a brand new “product” which represents a major step ahead for all users of the system.

5. **Car, ride and bike sharing**

   These are fast growing new mobility areas which until now have largely been looked at and developed along separate paths. But if we look at them as a new class of mobility options that share a number of common central characteristics and technologies, this approach could greatly accelerate development in all these areas. *(Our program references: World Carshare at http://www.carshare.newmobility.org, and World City Bike Collaborative at http://www.citybike.newmobility.org/)*
6. **New forms of shared transport (xTransit)**

Think shared-taxis for starters. Efficient, right-sized, ecological, technology-rich motor vehicles with drivers offering new levels of service and prices which provide the much needed bridge between fixed route scheduled mass transit and the driver-operated motor car. *(Our program references: xTransit Work Pad at http://www.xtransit.newmobility.org/)*

7. **Unified access schemes (The key to the new mobility system)**

Among the many great subtitle advantages of being a car owner/driver is that you have your keys in your pocket so that whenever you feel the itch you pop them in the ignition and off you go. By contrast, using public and other non-car options tends to be much less transparent in most places. If the future of the new mobility systems of our cities is to be able to offer a multiplicity of service options (the new mobility bouquet of services) they will have to be seen as easy to access as your car is today.

8. **Smart Growth/New Mobility partnerships**

Smart growth, new urbanism, new, richer (i.e., mixed use) and far denser patterns of settlement are what we can already see critical building blocks of our future – but until now the links between them and new mobility thinking and practices have been pretty weak. There is a lot that can be done to bring these two movements together in more synergistic and powerful ways.

9. **“Free” services**

It’s not necessarily going to be the case that all of these new services are going to be “paid for” in ways which might be recognizable today. It may even be that some, or possibly even the entire package, may be “free”. Think Google, think Skype and then turn back to your new mobility strategy. There are a lot of ways of paying for services other than through the fare box – and these options are well worth examining.

10. **Near term EV futures**

This final recommendation I offer here with considerable reserves - not least because I have not only been closely following developments in this field (critically) for a long time but also since I have had more than a decade of experience of driving an EV every day in Paris (best city car I ever had). The truth is that EVs per se do not do a great deal for much of what today is wrong with our city transport arrangements, but since they are getting so much attention we sure better have a well thought out position on this. Moreover, since there is a wave of developments gaining momentum here (and let’s not forget the enormous progress in process for cleaning up ICE, etc. technology), and because they work also as pattern breaks, it should be possible to hook a much broader range of strategic new mobility reforms to these projects in places where they come on line under their own steam.
The New Mobility Agenda: 2008 – 2012

New Mobility work in progress: 2008 - 2012

- The New Mobility Agenda - http://www.newmobility.org/
- New Mobility Dialogues - http://www.dialogues.newmobility.org
- World City Bike Collaborative - http://www.citybike.newmobility.org
- World Carshare Consortium - http://www.carshare.newmobility.org
- World Car Free Days Collaborative - http://worldcarfreedays.com
- Talking New Mobility – http://www.talking.newmobility.org
- New Mobility news – http://www.news.newmobility.org
- Helping car owner/drivers – http://www.newdrive.newmobility.org
- i am new mobility - http://www.iam.newmobility.org

Recent videos and films

- Contested streets – http://www.youtube.com/watch?v=YF4Q2badOng
- Unexpected interview - http://www.youtube.com/watch?v=VQASVz4xun8
- New Mobility Hubs intro - http://www.youtube.com/watch?v=4WNG0CkFCuE
- New Mobility video libraries – http://www.videos.newmobility.org
- StreetFilms (Livable Streets Network) - http://www.streetfilms.org
- Awareness test - http://www.youtube.com/watch?v=Ahg6qcgoy4
Ms. Sue Zielinski  
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Re: Global Networking in Support of New Mobility  

Dear Sue,  

On the occasion of your 11-12 June high-level brainstorming meeting on "New Mobility: The Emerging Transportation Economy", you asked me to speak to the topic of networking, research and collaborative partnerships for programs such as your sustainable mobility program -- drawing on our experience with open networking and building knowledge under the New Mobility Agenda for a number of years now. You asked about "building a learning community", but with the qualification that the goal is not to try to build up new structures, but rather to see how to better spot, link and make use of the considerable wealth of programs, sites, sources and resources already at work in our sector.

As you are aware, almost all of the work the last two decades under our New Mobility program has been carried out by and large with the collaboration and support of individuals and groups working in many different countries, types of organizations and parts of the world. Not to put too fine a point to it, we live by networking.

Our domain is, at first glance at least, relatively circumscribed: "sustainable transportation" - but behind the pure movement considerations lie the broader and more fundamental topic of sustainable cities, and sustainable lives. We talk about "new mobility", a phrase reduces to gaining access to what one needs in ways that are better suited to the strong and very different exigencies and priorities of the 21st century. Which brings us smack up against such closely related areas of policy and practice as: climate, local and global environment, energy viability, resource efficiency, geopolitical considerations, social equity, private and public economics, public health, and then at the end of this long line better, healthier and fairer transportation and access choices for all social and economic classes.

I am now pleased to report to you on this. I do it today in three parts: (a) the present note, (b) the website that we have created in support of this eventual future project at http://www.knowledge.newmobility.org, and (c) finally the latest version of the PowerPoint presentation of which I presented to you a far sorter earlier cut on 12 June in Ann Arbor and which you will find now at http://ecoplan.org/library/newmob-networks.ppt

To summarize the question (just to be sure we're on the right track):

Is there a requirement, a potentially useful role for a more creative and powerful system
Eric Britton  
Managing Director EcoPlan International

of interaction and exchange between some or all of these (and other) outstanding programs and their extensive knowledge bases?

**My preliminary observations on this:**

There is a huge amount of activity going on in this field (new mobility) in many places, though it is widely spread out, extremely varied in quality, quantity and focus, and at the present state of the art not really handy for consultation.

To use a common metaphor: we need to find ways to connect the silos.

But if one is to do anything at all in this area, we must have a firm understanding of how people go about accessing and putting all this to work in this fast-paced new century. How much detail do they need? How can we bring it to them in layers, tree like structures which give them a bit of information to get started but which then permit them to start to burrow into the topic without having to lose track of all that went before.

If we are looking for an analogy, what about the need for getting together to invent some kind of 21st century Dewey Decimal system to allow us to access the contents of our worldwide library?

There is very definitely a "new tools" vector that is worthy of closest attention. Most of us today are working with what in fact is a pretty old tool set (Moore's Law still holds) -- but the fact is that there are amazing new communications and linking tools available/needed that we should be putting to work.

Certainly we need to include full access not only to web sites, news groups, blogs, print in its variations, past and planned events in our areas of interest, but also to films, videos, sound, and images, as well as to games and other learning and playing devices that can be useful to sharpen the mind and bring up new perspectives. And 21st century communications options (full range thereof). In all this, if we are looking for models we would be consummately dumb not at least to try to understand by analogy what a "Google", "Skype", "Wikipedia", and even "Facebook", "LinkedIn", "YouTube", etc. new tools approach to this might give.

As I see it, there is both an information and an education-communications function to be served in our field. We need better working links between the main players: public sector players, researchers, local government, public interest groups and industry. But we also need much tighter linkages and let's call it "cultural consonance" with the media, old and new.
One stark reality is that if you look down our first listing here, you will note that each of these groups is extremely busy and very focused. They have their mandates, schedules, and responsibilities to deliver - all putting tough claims on their time and resources to do anything else. So whatever we come up with is going to have to fit in this tight environment.

And unless someone can convince me to the contrary, I for one would be quite opposed to the idea of setting up some sort of one more staffed program for this. I see this as an open collaborative venture with everyone pitching in, and someone very smart and capable coming up with some new cross-cutting software link and search solutions.

Finally the sense of urgency. The transport sector accounts for on the order of 20% of all greenhouse gases. We have the means to reduce this contrition at least when it comes to transport in cities by several percent each year, but we are not doing it because we have not made the strong case that is needed to sway policy maker and public attention. This project could be a great help in this creating the necessary now concerns for change.

To conclude: This is an important topic and we have at least the intellectual means and the tools needed to start to deal with it. What is needed is the resources to get it started and then step by step advanced as shown to be necessary and useful.

You know what we really need? It's someone who is willing to step forward and take on the task of becoming the DARPA of New Mobility. To shepherd the amazing discovery of an information highway that this time will carry and connect both people and electrons.

Who is going to have the foresight to take the lead?

Thanks for asking me such an interesting question Sue. Let's see what happens next.

Eric Britton
Managing Director, EcoPlan International
New Mobility Knowledge Environment Project Background:

The concept of new mobility or sustainable transportation is gradually gaining credibility as an alternative strategy for the policy, development and management of city transport systems worldwide. Starting from a very different series of basic conditions, premises and priorities to the transportation policies and practices that largely dominated the 20th century, these new approaches are increasingly being supported by a wide variety of leading practitioners, authorities, and institutions -- public, private and participatory -- in many parts of the world.

Despite this undeniable progress however, this approach is still heavily outmatched in many cities and parts of the world, in part because it advocates different approaches which are often regarded with doubt or suspicion by more conservative interests.

Fortunately there are a growing number of programs and institutions in different parts of the world that understand and are leading the charge with these new approaches: strategies and measures which are far better matched with the very different, historically unique and highly stringent requirements of this new century. One of the goals of this first-stage project is simply to identify the leading groups and approaches. For this you will find our latest short-list if you click here.

The goal of this just-starting open collaborative project proposal is to attempt to initiate a constructive dialogue among the people and organizations around the world who know the problems and possibilities best, to see if we can come to some sort of creative vision of what if any best next steps might be.

These first stages are being taken in hand by the New Mobility Partnerships as a public contribution -- and in doing this we note the sense of high emergency associated with this project that is driven by not only the long understood needs for radical transportation reform in our cities, but also and above all by the utmost urgency of the climate issues and just behind them the ever more pressing problems of energy supply, security and prices. It is for these reasons that this project takes on particular urgency and importance.

The project started to take shape in Spring 2008 with a series of exchanges between Sue Zielinski Managing Director of the Sustainable Mobility program of the Center for Advancing Research and Solutions for Society (University of Michigan) and Eric Britton of the New Mobility Partnerships in preparation for a high level brainstorming public/private conference on "New Mobility: The Emerging Transportation Economy" in which the idea was being turned around that our present information and "knowledge recuperation" tools were not keeping up with the urgent challenges we are presently facing. Britton was asked to lead a presentation and discussion on this during the 12 June 2008 conference, eventually entitled "Reinventing the Wheel (But not all by ourselves)".

The discussion was well received and eventually gave birth to this first stage project probe: The New Mobility Knowledge Environment (http://www.knowledge.newmobility.org/).
Personal Mobility and Global Climate Change

By Kevin Clemens

Purpose
The purpose of this paper is to report on the estimated carbon dioxide emissions produced by various the transportation modes that will be integrated into future systems of personal mobility.

Overview
The past 100 years has seen a wholesale change in personal mobility in the United States. Largely fueled by cheap and abundant fossil fuels, the widespread ownership of private vehicles has made it possible for workers to live in suburban and rural areas and commute long distances to their jobs. Before the wide scale adoption of the automobile for personal mobility, nearly all cities had a dense “downtown” business center that was usually close to water or rail transportation. Public transportation catered to these business districts, providing a way for commuters to travel to and from work. This changed after the turn of the twentieth century, and by the 1920s, automobile transportation and truck freight provided access from outside of this zone, and cities began to sprawl. Today, most personal travel takes place between urban and suburban areas, and urban areas that are highly dependent upon local motor transport systems for their supply of food, energy, raw materials and finished goods.

Until recently, petroleum for transport fuels and coal to make electricity have both been plentiful and inexpensive for the consumer but have resulted in significant costs to society. Uncontrolled burning of fossil fuels results in the release of air pollutants that pose a significant health hazard to the general population. The soot-charged streets of London resulting from the use of coal in the early 1950’s and the smog-choked Los Angeles basin during the 1960’s and early 1970’s provided graphic evidence of the need for careful use of fossil fuels. With regulations about the burning of coal and the adoption of mandatory pollution control devices on automobiles, the air quality situation in many major cities has improved dramatically. There are still many cities such as Beijing, however, where air pollution is a daily health risk, and in most cases this pollution is still a result of vehicle emissions and the burning of coal to produce electricity.

Global Climate Change- A New Challenge
In recent decades, evidence of another, more insidious, change in the Earth’s atmosphere due to the burning of fossil fuels has become evident. Fossil fuels exist because organic matter was trapped millions of years ago into geologic structures that slowly converted it to coal, oil or natural gas. This organic material was made up of plants and animals that had trapped carbon dioxide from the atmosphere and naturally sequestered it deep within the Earth. During the past 100 years, our modern technological society, in a quest for ever increasing amounts of energy, has released that carbon dioxide back into the atmosphere. The result is a buildup of carbon dioxide that traps the heat that would normally escape into space. This so-called greenhouse effect is causing a warming
of the Earth’s atmosphere resulting in a change to the global climate. Although the effect appears to be small, (about 1.33 degrees F in the past century, according to the 2007 report from the Intergovernmental Panel on Climate Change), it is enough to cause changes in weather patterns and produce dramatic changes in the global ecosystem. If left unchecked over the upcoming century, the further release of carbon dioxide will result in a significant rise in the sea level, wide scale desertification, droughts, species extinction, and an increase in severe weather events.

An Energy Intensive System

The mobility system that has developed for people and goods, particularly in the United States, is highly energy intensive and makes a significant contribution to atmospheric greenhouse gases such as carbon dioxide. Worldwide, the transport sector (including land, aircraft and sea sources) accounts for 23 percent of the total CO2 emissions from the combustion of fossil fuels [International Transport Forum, 2008]. The transport system is also highly dependent upon oil, the supply and price of which is becoming more unstable as reserves are depleted and geopolitical pressures disrupt easy access to the remaining oil.

In addition to its role in contributing to global climate change, the transportation system is also particularly susceptible to the results of changes in the global climate. Sea level rise for example, can inundate tunnels and roadways in low-lying coastal areas. Higher temperatures in summer months can cause buckling of steel railroad tracks and softening of road surfaces, resulting in greater damage from traffic. More frequent severe weather events can result in localized flooding, causing road infrastructure and bridges to collapse as they deal with water flow rates beyond their designed capacity. Although there will be some positive aspects to a warmer planet (e.g., less snow removal in Northern areas, the possibility of an open sea route through the Northwest passage from the Atlantic to the Pacific oceans), global climate change will, in general, present significant challenges to the transportation infrastructure. [National Research Council Special Report 290]

Future Needs

The transportation system that provides personal and freight mobility in the United States will need significant revision if it is to meet the challenges in the coming century. This revision will need to take place on several fronts:

- Creation of a transportation system that alleviates congestion and crowding in urban areas while providing equitable access
- Development of new energy technologies and a transportation infrastructure that drastically reduces the greenhouse gas emissions from personal vehicles, buses, trucks and aircraft
- Creation of new sources of liquid fuels that reduce the demand for oil
- Evaluation and modification of existing and new infrastructure to reduce disruptions caused by future global climate change events and their consequences
Transportation Modes and Carbon Dioxide Emissions

The following systems will be discussed and evaluated with respect to their greenhouse gas contribution, their range and usefulness, their ability to reduce oil usage, their susceptibility to global climate change and their ability to reduce urban congestion and integrate into a new mobility transportation network:

- Walking
- Bicycling
- Personal gasoline vehicles
- Motorcycles/scooters
- Personal diesel vehicles
- Personal gasoline/ethanol fueled vehicles
- Electric and Hybrid vehicles
- Personal vehicles using other fuels
- Transit bus
- Commuter rail/ subway

Walking

Walking would appear to be the ideal replacement for an energy intensive transportation infrastructure. Most people walk for at least a part of their daily commute, even if only to travel from the parking lot to their office or workplace. At a pace of three miles per hour, a walker in reasonably good condition could be expected to walk one mile during a reasonable 20 minute timeframe, limiting the practical commuting distance as a primary transportation mode. Weather also has a significant effect on commuting by walking as rain, storms, snow or excessive heat can limit or even cancel it as an option. For several decades, walkers were largely ignored when designing transportation infrastructure, and as a result many U.S. cities are not walker friendly. Street-level sidewalks, pedestrian walkways, highway overpasses and covered paths between buildings all enhance a city’s walkability.

Walking is susceptible to future global climate change due to increased fatigue and stress caused by increased temperatures, and as low-lying infrastructure (sidewalks and pedestrian walkways) become inundated by rising sea levels. Walking is incredibly adaptive to change, though, as it requires the least dedicated infrastructure.

Walking would seem to be greenhouse gas neutral, as the carbon dioxide exhaled by an exercising human being was originally sequestered by a living plant before being consumed and returned to the atmosphere through human metabolic activity [CDIAC 2008]. Approximately 94 kCals of energy are required to walk a mile at a three mile per hour pace [MET Intensities]. According to the U.S. Department of Agriculture (USDA), the average human being requires 2,000 calories of food energy for general metabolism each day, but many in western society consume significantly more calories (more than 2,700 calories) each day [USDA 2001-2002]. The Center for Disease Control (CDC) reports the average calorie intake for a U.S. male is 2,693 calories [CDC 2007]. If no additional food calories are consumed to offset the extra energy output from walking, then commuting a mile by walking does not add additional carbon dioxide to the atmosphere.
If the energy required walking a mile is offset by consumption of additional food calories, the CO₂ output picture changes. Our modern food infrastructure adds significantly to the carbon dioxide levels released to produce food energy. A person eating a typical American diet releases 0.39 pounds of CO₂ while burning the 94 calories needed to walk a mile [Earth Interactions]. This CO₂ is not exhaled by the walker of course, but was emitted in the process of creating the food from which the walker obtains energy. A large amount of the food’s CO₂ comes from the use of petroleum in farm operations, for fertilizer, for packaging and food processing and for transportation to the grocer’s shelves.

Dietary choices dramatically alter the amount of CO₂ generated by a person. Foods such as beef [Pacific Institute] add significantly to CO₂ emissions and are an inefficient way to generate food calories. It is estimated however that a vegan diet (particularly using locally grown vegetables that don’t require much transportation) will result in approximately 0.08 pounds of CO₂ per mile walked [Earth Interactions].

This brief analysis of the impact of the foods on the carbon dioxide emissions of transportation highlights the importance of a system’s approach to the study of future personal mobility. It isn’t simply about changes to the transportation infrastructure, but a holistic examination of how the world works.

**Bicycling**

Bicycles multiply a human’s work, allowing for greater efficiency. Whereas walking a mile requires 94 kCals at three miles per hour, riding a bicycle requires only 34 kCals per mile while traveling at ten miles per hour [MET Intensities]. This greatly expands the range possible for a 20-30 minute commute, while reducing the energy expenditure of the commuter when compared to walking. Bicycles frequently share the road with automobiles, buses and other transportation systems; and this can pose safety problems unless special bike lanes are created. Bicyclists face many of the same weather related limitations as walking commuters, and the consequences of sea level rise and global temperature increases are also similar.

Because bicycling requires significantly less energy per mile when compared to walking, the CO₂ generated in the creation of this food energy is also less at about 0.14 pounds of CO₂ per mile for a typical U.S. diet [Earth Interactions]. A vegan diet reduces CO₂ output to an almost negligible 0.03 pounds per mile for a bicycling commuter [Earth Interactions]. This analysis neglects the amount of CO₂ generated when the bicycle is manufactured.

**Personal vehicles (gasoline)**

The reality in the U.S. is that people don’t commute by walking or bicycling; they get to work by driving a gasoline powered automobile. According to a 2006 U.S. Census Bureau survey, 86.7 percent of all U.S. commuting is done by the personal car, light truck or sport utility vehicle (SUV).

Commuting by automobile became popular in the 1950s and 60s as families moved to suburbs and farther from the workplace. The average commute in the U.S. is 16 miles and takes 25 minutes [ABC News 2005], although cities like Los Angeles are known for average commutes that can be an hour or longer.
One gallon of gasoline contains 31,500 kCals of energy and about 2,421 grams of carbon. CO₂ emissions from gasoline total 19.4 pounds/gallon [EPA420-F-05-001]. Thus, it is easy to calculate that when gasoline is burned in a typical automobile in the U.S., achieving 20 miles per gallon, approximately 0.97 pounds of CO₂ are released for each mile traveled. The fuel economy of a personal vehicle affects the amount of CO₂ released per mile. A sport utility vehicle or full-sized pickup truck achieving 15 miles per gallon, for example will release 1.29 pounds of CO₂ per mile, while an economy car getting 35 miles per gallon will release 0.55 pounds of CO₂ per mile traveled. These analyses neglect the greenhouse gas emissions generated in the manufacture and disposal of the vehicles. Reducing travel also has a positive effect of greenhouse gas emissions. In 2007, Americans traveled 3 trillion miles by car [DOT Traffic Volume Trends], but in the first half of 2008, travel by car was down 2.1 percent according to the U.S. Department of Transportation [DOT 2008], in large part due to the price of gasoline, which has risen dramatically to more than $4.00 per gallon.

Although personal vehicles contribute to global climate change, they are also affected by the effects of warming and subsequent sea level rise. Road infrastructure in low-lying coastal areas is particularly susceptible to flooding and to being washed away during storm-surge. Higher average temperatures can soften road materials, causing damage by highway traffic and reducing a road’s life expectancy. In Northern areas, higher average temperatures may result in more or less snow, depending upon moisture levels and weather patterns, either increasing or decreasing the costs associated with snow-removal and highway maintenance.

Motocycles/scooters
In many parts of the world, motorcycles and motor-driven scooters are viable means of transportation for commuters. Where the climate is moderate, year-around commuting on two-wheels is a possibility, while in the northern parts of the country, such commuting is more seasonal. Commuting by motorcycle or scooter limits the amount of cargo that can be carried and increases the need for both weather protection and protective clothing to reduce injury in the event of a fall or collision with another vehicle. Riding a scooter or motorcycle safely also requires a certain level of attention, physical coordination, and proficiency that not all of the general commuting public may wish to achieve. A typical small motorcycle or scooter (200-cc or smaller) can get 55 miles per gallon of gasoline, resulting in a CO₂ emission of 0.3 pounds per mile. Two-wheeled vehicles are best when used for commuting in urban settings where their small size, maneuverability and ease in parking make them a viable choice, at least during good weather. Because they share the road with other personal and commercial vehicles, two-wheel vehicles are subject to the same effects global climate change as these vehicles.

Personal vehicles (diesel)
In Europe and Asia, diesel automobiles and sport utility vehicles are common, while in the U.S. they are relatively rare. One gallon of diesel fuel contains 34,950 kCals of energy and 2,778 grams of carbon, and burning a gallon of diesel fuel produces 22.2 pounds of CO₂ (about 14 percent more than gasoline) [EPA420-F-05-001]. At equal fuel economies, a diesel engine produces about 15.25 % more CO₂ per mile, or about 1.12 pounds per mile for a vehicle achieving 20 miles per gallon on diesel fuel [EPA420-F-05-
Because diesel engines are more efficient due to higher compression ratios and no throttle plate, and because they burn a higher energy fuel than gasoline engines, they can achieve 20% or more improved fuel economy figures and thus can actually reduce the amount of CO₂ per mile emitted. Diesel fuel costs nearly $5.00 in 2008, and economics have cooled the interest in diesel passenger vehicles in the U.S.

**Personal gasoline/ethanol fueled vehicles**

Ethyl alcohol, or ethanol, has existed as an automotive fuel since the early 1900s. By the mid-1970s, Brazil had switched an entire fleet of cars from gasoline to biofuel ethanol made from sugar cane. In the U.S., ethanol is principally made from corn and is mixed as a 10% blend with gasoline as an anti-knock additive. Ethanol can also be blended with gasoline to produce E85, an 85% mixture of ethanol. To use this fuel in vehicles requires some modification to the fuel system to create a Flex-Fuel Vehicle (FFV) that can operate on a range of ethanol and gasoline mixtures. There are approximately 6 million Flex-Fuel vehicles on the road in the U.S., and the number is increasing. In 2007, the U.S. produced 5.9 billion gallons of ethanol from corn, and The Energy Independence and Security Act of 2007 has mandated that 36 billion gallons of renewable fuel (of which 21 billion is required to be biofuel) be a part of the fuel mix by 2022 with at least 15 billion gallons of ethanol produced yearly by 2015.

Ethanol produced from corn can be relatively energy intensive. Processing corn uses fossil fuels to produce fertilizers, operate diesel farm machinery and to convert the corn into ethanol. Future ethanol production from cellulosic materials such as hay, wood chips or specifically grown biofuel crops promises higher ethanol yields per acre at lower energy investments. Ethanol contains less energy per gallon than does gasoline (21,270 kCals), but engines can run more efficiently with the higher compression ratios allowed by ethanol’s anti-knock properties. The following table gives an indication of the amount of CO₂ per mile emitted by ethanol biofuels for a 20 mile per gallon vehicle [EPA 2007]:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Pounds of CO₂ per mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.97</td>
</tr>
<tr>
<td>Corn Ethanol</td>
<td>0.76</td>
</tr>
<tr>
<td>Sugar Cane Ethanol</td>
<td>0.43</td>
</tr>
<tr>
<td>Cellulosic Ethanol</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The feedstock and the process by which ethanol is produced and the way that land is used to grow the feedstock have great impact on its viability to reduce greenhouse gas emissions.

**Electric and hybrid vehicles**

Electric cars were popular in the early 1900s. They were excellent for use around town, were quiet, produced no pollution and were easy to operate. The electric car’s biggest problem was its limited range caused by the amount of charge that its battery was capable of carrying. Gasoline engines, whose range was limited only by the amount of gasoline carried on-board, eventually replaced the electric car. In an effort to reduce exhaust emissions in the 1990s, the State of California mandated that a percentage of
vehicles sold by manufacturers had to be electric vehicles. California backed away from this mandate when it became clear that battery technology still wouldn’t allow an acceptable range for most consumers. The electric car was replaced by the hybrid vehicle.

The concept of a gasoline hybrid electric vehicle has been around for more than a hundred years, but it wasn’t until the beginning of the 21st Century that such vehicles became commercially available. Honda and Toyota (with its successful Prius) have dominated the market, although GM and Ford have recently produced several hybrid models. The technical details vary with different models, but the objective is to use an electric motor and battery to augment a regular gasoline engine to improve fuel economy and reduce the CO2 emissions from the vehicle. By 2010, a new form of plug-in hybrid will be available from GM (Volt) and Toyota (Prius) that will allow charging from the electric power grid and provide electric-only operation for a limited range before the gasoline engine kicks in to extend the range of the vehicle to acceptable levels.

Hybrid vehicles can be expected to achieve fuel economy levels of at least 50 miles per gallon, at which point CO2 emissions will be 0.38 pounds per mile or better. The carbon dioxide missions from plug-in hybrid and electric vehicles depend dramatically upon the source of electricity to the power grid. A plug-in hybrid operating with electricity generated from a typical coal-fired plant results in a CO2 level of 0.7 pound per mile. [Tree Hugger] If the electricity comes from a nuclear plant or from wind or solar energy, the CO2 levels drop to 0.33 pounds per mile or less, depending upon how much gasoline operation is required [Tree Hugger].

**Personal vehicles using other fuels**

Several other fuels show promise for the future. Liquefied Petroleum Gas (LPG) and Compressed Natural Gas (CNG) are fossil fuels that burn slightly cleaner than gasoline and diesel. They require a different fuel system than is currently in use but have been well-proven to operate with a minimum of problems. As with other fossil fuels, their availability will also be limited over time.

Hydrogen has been proposed as a solution to both limited future petroleum supplies and to greenhouse gas emissions. Hydrogen can be burned in an internal combustion engine or used in a fuel cell to produce electricity. Either process is extremely clean and produces no carbon dioxide. Unfortunately, current commercial processes to produce hydrogen use natural gas as a feedstock and produce significant quantities of CO2 as a by-product.

Coal-to-Liquids (CTL) is a process by which coal is converted into a petroleum substitute. Gasoline or diesel fuel can be synthesized through such a process. Huge amounts of carbon dioxide are created through the CTL process, and capturing and sequestering the CO2 in geologic storage is the only realistic way in which this process can be viable. Unfortunately, there is currently no feasible process by which this amount of CO2 can be sequestered.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Pounds of CO2 per mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline (20 mpg)</td>
<td>0.97</td>
</tr>
<tr>
<td>Liquefied Petroleum Gas (LPG)</td>
<td>0.78</td>
</tr>
<tr>
<td>Compressed Natural Gas (CNG)</td>
<td>0.69</td>
</tr>
<tr>
<td>Hydrogen Gas</td>
<td>0.57</td>
</tr>
</tbody>
</table>
Carbon dioxide emissions from public transportation are particularly hard to estimate. Local city buses, for example, vary widely in their ridership. A bus is empty as it leaves the bus barn until it picks up its first passengers for the day. During rush hour, buses may be filled to capacity, but during slow times the bus may have just a few passengers. For a city bus the CO$_2$ emissions are estimated to be 0.71 pounds per passenger mile [Cato Institute].

Because buses travel on regular roadways (or sometimes on special bus lanes adjacent to roadways) they are susceptible to the same effects from global climate change and sea-level rise as are other road users. The advantage of buses over other public transportation is their adaptability; buses can be rerouted or new routes can be created as road and social conditions change, providing advantageous flexibility.

Like buses, ridership of commuter rails varies greatly with the time of day and the route. Commuter rails and subways are huge public works projects that require years to design and build and which can greatly disrupt other transportation infrastructure during their construction. Carbon dioxide emissions per person depend greatly upon ridership. For a subway or light commuter rail the CO$_2$ emissions are estimated at 0.36 pounds per passenger mile [Cato Institute].

More than any other transportation system, rail cars and subways will be affected by global climate change. Underground tunnels near costal areas will be endangered by sea-level rise, and existing rail bridges and infrastructure will be threatened by storm water flow amounts exceeding their design parameters. Increased ambient temperatures can contribute to rail buckling, causing accidents and requiring additional maintenance. As conditions change, rail and subway lines will prove to be less adaptable to meet new requirements.

Transportation systems that emphasize personal mobility must take into account a future that includes global climate change. Transportation accounts for significant amounts of the greenhouse gas emissions that contribute to climate change. New mobility systems that include a variety of transportation modes must consider the emission of greenhouse gases such as carbon dioxide and how such emissions can be minimized for the greatest number of commuters, while still attaining other goals such as reduced congestion and optimized travel time. In addition, transportation is susceptible to change and disruption as a consequence of global climate change and these changes must be a part of planning for the future. The complexities of developing this new infrastructure will require a systems approach that goes beyond simply examining transportation systems to include the entire social fabric of modern and emerging societies.
## APPENDIX- Summary of Carbon Dioxide Emissions

<table>
<thead>
<tr>
<th>Transportation Mode</th>
<th>Pounds of CO₂ per mile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Walking</strong></td>
<td></td>
</tr>
<tr>
<td>U.S. diet</td>
<td>0.39</td>
</tr>
<tr>
<td>Vegan diet</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>Bicycling</strong></td>
<td></td>
</tr>
<tr>
<td>U.S. diet</td>
<td>0.14</td>
</tr>
<tr>
<td>Vegan diet</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Passenger vehicle-gasoline (20mpg)</strong></td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Passenger vehicle- compact gasoline (35 mpg)</strong></td>
<td>0.55</td>
</tr>
<tr>
<td><strong>Passenger vehicle- gasoline SUV (15 mpg)</strong></td>
<td>1.29</td>
</tr>
<tr>
<td><strong>Passenger vehicle diesel (20 mpg)</strong></td>
<td>1.12</td>
</tr>
<tr>
<td><strong>Passenger vehicle- ethanol (20 mpg)</strong></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>0.76</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>0.43</td>
</tr>
<tr>
<td>Cellulosic</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Motorcycle/scoter (55 mpg)</strong></td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Passenger vehicle- hybrid (50 mpg)</strong></td>
<td>0.38</td>
</tr>
<tr>
<td><strong>Bus (per passenger mile)</strong></td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Train/subway</strong></td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Passenger vehicle (20 mpg)</strong></td>
<td></td>
</tr>
<tr>
<td>Hydrogen gas</td>
<td>0.57</td>
</tr>
<tr>
<td>Liquid Hydrogen</td>
<td>1.03</td>
</tr>
<tr>
<td>LPG</td>
<td>0.78</td>
</tr>
<tr>
<td>CNG</td>
<td>0.69</td>
</tr>
<tr>
<td>Coal-to-Liquid with sequestration</td>
<td>1.01</td>
</tr>
<tr>
<td>Coal-to-Liquid without sequestration</td>
<td>2.12</td>
</tr>
</tbody>
</table>
REFERENCES


ABC News 2005- ABC News February 13, 2005

EPA420-F-05-001- Emission Facts: Average Carbon Dioxide Emissions Resulting from gasoline and Diesel Fuel- Environmental Protection Agency (February 2005) EPA420-F-05-001


DOT Traffic Volume Trends- Department of Transportation http://www.fhwa.dot.gov/ohim/tvtw/tvtpage.htm


Mega-Challenges Confronting Sustainable Urban Modernity

By Thomas N. Gladwin

The opening line of A Tale of Two Cities by Charles Dickens--“It was the best of times, it was the worst of times…”--portraying life in London and Paris during the French Revolution--applies equally well to today’s burgeoning cities throughout much of the developing world. Whether it is Lagos, Mumbai, Sao Paulo, Karachi or Shanghai, life within or on the periphery of such cities mixes economic opportunity with deprivation, social solidarity with exclusion, and ecological blessings with burdens. With this year marking the epochal transition of humanity from a rural to a majority urban species, it is a propitious moment to ponder how the future of global urbanization (to occur predominately in the low and middle income countries of Asia, Africa and Latin America) may evolve over the next few decades in regard to size, velocity, shape and functioning. The big question is whether the urbanization of today and that to come will lead the world toward or away from sustainability (i.e., achieving an optimal scale of resource throughputs within the regenerative and absorptive capacities of “life-supporting” ecosystems; optimal distribution of resources both within and across generations based on ethical criteria of equity and sufficiency; and with scale and distribution established, optimal allocation or division of resources shaped by the logic of market efficiency).

The dawning of the urban millennium has been marked by a prodigious outpouring of projections and assessments of urban futures from international organizations such as UN-Habitat, UN Population Fund, World Bank, UN Environmental Programme, Intergovernmental Panel on Climate Change, Worldwatch Institute, OECD, International Energy Agency. etc. [NOTE: key references for the statistics reported herein can be obtained by emailing tgladwin@umich.edu]. Table 1 provides a summary snapshot of long-term global projections recently provided by these organizations of relevance to urban evolution. These are typically “business as usual” projections based on recent experience, assumptions of linearity and continuity, masking of huge regional disparities, and “tunnel vision” disregard for complex “whole system” dynamics and interdependencies.

[Table 1 about here]

When put together, the projections entail huge “impossibilities.” Can the world’s cities really grow their fossil fuel-based energy consumption massively in the wake of the end of cheap oil and climate change? Can the future or urbanization really be concentrated in the world’s coastal zones growing increasingly vulnerable to extreme freshwater scarcity, storm surges and sea-rise levels induced by climate change? Can cities in low income nations really double their urban populations with mainly very poor, old and young people in the absence of vast increases in employment, income and tax revenue? And can we really double or triple the physical size of the world’s cities while irreversibly liquidating the stocks of natural capital upon which such growth ultimately depends? Inconsistency in charting urban futures is to be expected given that forecasters are
dealing with a confluence of unprecedented and very complex trends (e.g., population aging, urbanization of poverty, coastal ecosystem degradation, climate change, massive sprawl, decoupling of urbanization from industrialization and wealth creation, etc.) without parallel in the history of humanity.

This article, adapted from an academic address at the June 2008 “New Mobility” Conference organized by the University’s “Sustainable Mobility & Accessibility Research and Transformation” [SMART] Project, briefly surveys eight “mega-forces” vastly complicating or reducing the potential of achieving sustainable urbanization (mainly in the developing world) and concludes with an integrative systems model causally connecting the eight forces suggesting possible urban futures quite different from those currently anticipated. A rather “doomy and gloomy” picture is forecasted. In the absence of radical efforts to alleviate poverty and to promote environmental sustainability, the lives of of hundreds of millions of urban dwellers under this painted scenario, to borrow from Thomas Hobbes The Leviathan (1651), could become increasingly “solitary, poor, nasty, brutish, and short.”

**Urban Population Growth:** UN demographers project that the world’s population will increase by 2.5 billion from today to a total of 9.3 billion by 2050, with more than 95% of this growth expected to occur in today’s developing nations. The population living in urban areas is projected to expand by 3.1 billion during this time period due to immigration, natural increases from relatively high fertility rates of those in poverty and reclassification. Roughly 75% of humanity is thus predicted to be urban by 2050 as compared to 50% today. The urban population of developing nations is expected to double to 4 billion people by 2030, increasing at the rate of 70 million per year. The influx of “climate change refugees”, as discussed below, may take these figures much higher. Only 22% of this growth is expected to occur in cities with more than 5 million citizens; about half of the urban expansion is likely to occur in smaller and newer “edge/infill/satellite” cities of less than 500,000 inhabitants, probably least equipped to effectively manage rapid expansion. The extraordinary scale of urban growth, particularly in Africa and Asia, was recently captured by Enrique Penalosa, the former mayor of Bogota, at the World Urban Forum: “these 2 billion new urban inhabitants will require the equivalent of planning, financing and servicing facilities for a new city of 1 million people, every week, for the next 30 years.”

**Population Aging:** The demographic transition from high to low fertility and mortality throughout much of the world is producing unprecedented population aging, especially in urban areas. The UN projects that the proportion of people aged 60 and over will increase from about 10% today to over 20% of total population (2 billion people, nearly a third of urban population) by 2050. The aging trend is most advanced in the industrialized world, particularly Europe, but the pace of population aging is most rapid (and most compressed) in the developing world. China and India together already account for one-third of the world’s older citizens. Urban areas house 51% of the world’s older persons today, but the figure is likely to rise to 62% by 2025 as a result of rising longevity and rural-to-urban migration. Combined with aging, cities of the South will also be confronting a “youth bulge”—some 60% of all urban dwellers are likely to be
under the age of 18 by 2030. The rapidly declining worker to retiree and youth ratio (i.e., “the dependency burden”) can be expected to strain the fiscal, health, educational and pension systems currently in operation in most major cities. We can also anticipate the necessity of radical shifts of urban social and physical infrastructure if cities are truly to become caring place for seniors and youngsters.

**Poverty/Slum Growth:** While globally the majority of the poor are today found in rural areas (which will likely remain true for a few decades to come), the locus of poverty is rapidly shifting from the countryside to cities. UN-Habitat estimates that over 1 billion people now reside in urban slums, often squalid, unhealthy areas without water, sanitation, durable housing, public services and secure tenure. 63% of these slum-dwellers are found in Asia, 22% in Africa and 15% in Latin America/Caribbean; slum populations are growing faster than urban populations in general and the fastest in Sub-Saharan Africa at the rate of 4.53% per year. In the absence of radical policy shifts, UN-Habitat predicts that some 2 billion people (about one-half of the urban population in developing countries) could be struggling to live in slums, particularly in Africa and Southern Asia, by 2030 as a result of poverty traps, persistent unemployment, elite neglect, bypassing of “risky” urban areas by global investors, and substantially increased in-migration pressures. UN-Habitat research reveals that “there is little or no planning to accommodate these people or provide them with services.” Anna Kajumulo Tibaijuka, Director-General of UN-Habitat, warns of the consequences: “In this global village, someone else’s poverty very soon becomes one’s own problem: of lack of markets for one’s products, illegal immigration, pollution, AIDS, other diseases, insecurity, crime, fanaticism, terrorism…we can no longer ignore the plight of slum dwellers…we do so at the risk of massive social exclusion with all of its attendant consequences for peace and security.”

**Urban Physical Expansion:** Numerous recent studies indicate that the vast majority of the world’s cities are spreading out in built-up area faster than they are growing in population. A recent World Bank study (Angel, et. al., The Dynamics of Global Urban Expansion) estimates that average urban densities over the past decade have been declining at an annual rate of 2.2% in developed countries and 1.7% in developing countries. Rising real incomes, falling real transportation costs and enhanced accessibility via information/communications technology appear to explain much of this decentralization and fragmentation of metropolitan growth. If such “diffuse urbanism” continues, the world’s cities could grow 2.5 times in built-up area by 2030, consuming an additional 700,000 km2 of land area (i.e., a tripling of built-up area in developing nations to accommodate the doubling of urban population and a 250% increase in land consumption by cities in developed nations with only a 20% projected increase in urban population). As noted below, more than doubling the spatial size of the world’s cities over the next few decades would have enormous adverse effects on the health and integrity of life-supporting natural systems, particularly if most of the expansion is situated in fragile coastal zones. As with slums, the Angel study sadly concludes that “few governments in the developing world are actively preparing for urban population growth, even though it is now generally accepted that slowing it down or reversing the
Coastal Densification: The World Resources Institute estimates that about half of world population currently lives within 200 km of a coast and about a third (2.2 billion) lives within 100 km of a coast. Almost half of the world’s cities with populations over 1 million are located within this 100 km zone and about half of the world’s smaller cities with less than 500,000 are located within 50 km of the coast. Average population densities in the world’s coastal zones are three time higher than world average. Large positive productivity and quality of life effects of coastal proximity have served to concentrate employment, income and urbanization along the coasts; in China alone, an estimated 100 million have moved from inland to coastal locations over the past 20 years. So while cities are de-densifying, they are sprawling throughout coastal zones creating seemingly endless urban zone corridors (such as the Boston to Washington, D.C. corridor in the U.S. northeast). Estimates of future coastal population growth vary widely, ranging from 750 million to over 4 billion over the next few decades. As explored below, the potent mix of climate change-induced storms and sea-level rise, along with severe water scarcity (coastal zones currently have less than 10% of global renewable freshwater supplies) and exponential degradation of fragile coastal ecosystems could profoundly reduce the attractiveness of coastal living in the near future.

Freshwater Stress: The world’s freshwater resources are under rapidly growing pressure. Global freshwater use has tripled over the past 50 years; demand for water resources is growing at twice the rate of population growth; long-term per capita water availability has dropped by a third since 1960; and two-thirds of humanity inhabits areas that today receive less than 25% of annual rainfall. The UN conservatively estimates that 1.1 billion people still lack access to water supply services and 2.6 billion lack sanitation. If current supply and demand trends continue, at least 3.5 billion people (49% of world population) could be living in water-stressed conditions by 2025, with “stress” defined as per capita water availability of 1700 cubic meters or less per year. One-third could be in regions facing water “scarcity, i.e., less than 1000 m3 freshwater availability per capita/year. Regions forecast to be hit the hardest include the Middle East, Central Asia, North Africa, South Asia, China, Australia, Western U.S., and Mexico. Water availability constraints are posed by population growth, rising incomes, groundwater depletion, pollution, expanding farm irrigation, and most profoundly, by climate change, which is projected to decrease precipitation, river runoff and water availability in general in many subtropical, arid and semi-arid regions. Many existing mega-cities (e.g., Los Angeles, Mexico City, Cairo, Karachi, Bombay, New Delhi, Calcutta, Beijing, Shanghai) confront massive water challenges, as do the hundreds of smaller cities projected to emerge in the coastal zones of Asia and Africa lacking dedicated supplies, delivery infrastructures, fiscal resources and management systems.

Ecosystem Degradation: Today’s cities occupy 3% of the Earth’s land surface, house 50% of world population, generate about 75% of world gross national product, consume 60% of the world’s water, and emit 80% of global greenhouse gas emissions. Cities obviously appropriate the ecological output and life-support services provided by both
proximate and distant ecosystems. The city of London, for example, has an estimated “ecological footprint” (i.e., the area of biologically productive land and water required for its consumption of food, fiber, timber, land, and disposal of wastes and pollution, including carbon sequestration) 293 times its physical size (an area roughly twice the size of all of the U.K.) and 42 times the city’s own “bio-capacity” for resource generation and waste absorption. The World Wildlife Fund’s latest Living Planet Report estimates that the world as a whole is already using the planet’s resources faster than they can be renewed by a factor of 30%. Projected population and economic growth trends (e.g., the OECD predicts that world gross domestic product will double by 2030 and triple by 2050) suggests that by 2050, humanity’s demand on nature could be twice the biosphere’s productive capacity. With current urban “ecological footprints,” this would imply that cities would survive only through a vast global appropriation and near total liquidation of the natural capital of the planet’s hinterlands. This is obviously a socially, economically, politically, and ecologically impossible scenario. As documented in the UN Millennium Ecosystem Assessment, the bulk of today’s cities are situated in the planet’s most fragile and most highly threatened [coastal] ecosystems, nearly all in a state of exponential degradation. Reductions of urban footprints on the order of 80% may thus be necessary to secure a sustainable human urban future.

**Climate Change:** Urban centers in low and middle income countries, where the most rapid urbanization is projected, particularly where situated in coastal zones and riverine areas, are forecast by the Intergovernmental Panel on Climate Change (IPCC) to be increasingly vulnerable to the adverse effects of global climate change. Cities along the east coast of China and India, as well as in the Caribbean region, Gulf Coast of the U.S. and Central America, are especially likely to experience an increase in the frequency and intensity of extreme weather events such as heavy rainstorms, cyclones or hurricanes. IPCC forecasts of sea level rise due to thermal expansion and ice melt ranging from 18 to 81 cm (or even possibly up to 5-6 meters with abrupt melting of Greenland’s ice sheet or collapse of the West Antarctica ice sheet) during this Century could wreck havoc on the 634 million people living in the world’s “low-elevation coastal zones” (less than 10 meters above sea level), predominately in South and East Asia, via flooding, coastal erosion and wetlands inundation. As noted above, the IPCC predicts a substantial decrease of rainfall, along with increased evaporation and saltwater intrusion into coastal aquifers, greatly boosting freshwater stress in the already semiarid and arid areas such as the Mediterranean basin, western U.S., Southern Africa and Northern Brazil. Estimates of the number of coastal urban residents at serious risk from climate change-induced storms, sea level rise, reduced water supplies, heat waves, spread of infectious diseases and so on range from 500 million to 2.75 billion. Inland impacts of climate change, including drought, food and water shortages, and conflicts over scarce resources, could induce a vast increase in forced migration from the countryside to cities, both within countries and across borders. Estimates of the number of “climate refugees” on the move over the next few decades range from 150 to 900 million. The big uncertainty is where they will try to go. Numerous analysts forecast massive movement of “climate refugees” into the flood plain and steep slope slums of coastal cities, preordaining a vicious cascade of human climate tragedies. “Business as usual” projections of energy demand, fossil fuel use and greenhouse gas emissions out to 2030 and 2050 from the International
Energy Agency take the world way beyond the 2 degree Celsius rise of mean global
surface temperature above pre-industrial levels deemed necessary for avoiding “runaway
climate change” inducing the urban chaos projected above. Clearly both old and new
cities will need to drastically reduce their GHG emissions and dramatically increase their
adaptive capacities to reduce vulnerabilities to climate change impacts.

**A Systemic Look Forward:** When you “Google” for quotes on “the modern city,” one
modern city is the *locus classicus* of impossible realities.” While wildly out of context,
this conception nicely captures the essential predicament confronting developing nation
cities. The eight “mega-forces” reviewed above do not operate independently, but rather
function as a tightly intertwined set of interdependent relationships. The “urban-
ecological-economic-sociological-political” nexus constitutes a “complex adaptive
system” characterized by emergence, path-dependence, co-evolution, nonlinearity, self-
organization, delays, irreversibility, tipping points and surprise. The future of global
urbanization thus profoundly challenges understanding as well as prediction. Figure 1
provides a very crude “causal loop diagram” capturing the “feedback dependencies”
operating among the eight mega-forces outlined above based on solid theory and
empirical evidence. The arrows represent causal relationships; the polarities next to each
arrowhead indicate whether the effect is positively related (S for same direction) or
inversely related (O for opposite direction); and the double hash marks on an arrow imply
substantial delays in time or space. Typically employed in the early qualitative stages of
developing a rigorous mathematical system dynamics model, causal looping forces a
modeler to expose his or her causal assumptions to external review and critique.

[Figure 1 about here]

While highly simplified, the 37 causal relationships charted in Figure 1 highlight the
extraordinary “dynamic complexity” (i.e., separation of cause and effect in time and
place) at work in the dynamics of global urbanization. While detailed analysis lies
beyond the scope of this brief article, the “patterns that connect” suggest some
foundational insights about the probable future of developing nation cities. First, while
every mega-force in the system is both causal and consequential, some of the forces
appear to be more potent in driving system behavior. The interactive forces of urban
population and physical growth approaching or exceeding the limits of freshwater
availability, carbon sequestration capacity and ecosystem integrity emerge as the
“fundamental drivers” of the fate of the whole system. Other forces such as population
aging, slum growth and coastal densification are largely consequences of the driving
forces or other variables lying outside of this eight mega-force system, such as medical
care improvements. A major implication is that long-lasting improvements in the healthy
functioning of a complex system rarely emerge from “palliative” solutions targeted at
consequences (e.g., boosted “social safety nets” for those in poverty) while the
fundamental drivers of such consequences are still exponentially in force. And second,
some two-thirds of the relationships and derivative “causal loops” portrayed in this
system move in the same causal direction, implying a very powerful, self-reinforcing,
accelerating and “policy-resistant” vicious cycle of dysfunctional and unsustainable
urbanization. The only substantive “balancing or regulating” causal loops bringing stability to the system are either weak or quite delayed in effect (e.g., long-term increases in environmental stress-associated mortality or morbidity reducing aging and population size and therefore urbanization).

Our cursory trend and systems analysis, in the absence of profoundly pro-poor/female/youth/livelihood/renewable energy/compactness/eco-efficiency/self-sufficiency/adaptive capacity policies and interventions portends cities of “darkness rather than light” as once imagined by urban futurists. The urban world over the next few decades under this scenario has the composition of cities growing older, younger, poorer and more divided; the resources available to city dwellers growing more scarce and costly; the physical structure of cities simultaneously growing more sprawled and crowded; and the living conditions in cities becoming much hotter, drier, contagious, insecure and conflictive. With substantial delays, as illustrated in Figure 1, the forces of devastating climate change and explosively unstable slum growth could combine to radically reduce “livability” in coastal urban regions, leading to pressures for a massive migratory shift toward more climate resilient, water plentiful, socially secure, and economically prosperous inland and higher ground…such as Ann Arbor! Whether the world permits or attempts to block this rational and powerful search for human security will surely induce a wave of unanticipated consequences. Moving forward, our only hope as citizens and scholars, is to abide by the wisdom suggested by Antonio Gramsci, the Italian philosopher and revolutionary, that “the challenge of modernity is to live without illusions and without becoming disillusioned.”

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Figure 1: Causal Loop Diagram
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A Model of Social Inequity and Accessibility in Detroit

Jonathan Brown
Krista Gullo
Chris Sorensen

Professor Tom Gladwin
John Gearen
NRE 550
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“Transit once held promise as a means for advancing larger social goals. Congress embraced transit as a legitimate means of redistributing wealth, as an acceptable counterbalance to the damages imposed by a transportation system skewed towards the automobile …Despite a commitment to social goals over several decades aimed at providing mobility for people who cannot drive, other goals have taken over in prominence. But transit policy is slowly, almost imperceptibly, shifting away from its broader social purposes. This shift way from meeting social goals toward the more narrow purpose of relieving traffic congestion, from achieving equity toward merely efficiency, is now influenced by a neoliberal political agenda that separates the social from the economic…” (Grengs, 2005, pg. 52).

Introduction

With growing congestion, emissions, and accidents, as well as declining accessibility the global trajectory for mobility is commonly accepted to be unsustainable (WBCSD 2001). Taking a systems view, the largest barriers (and leverage points) to achieving sustainable mobility are ease of access to the different mobility modes, and the equity of access for people across all demographics (Appendix C). Therefore, this report focuses on the two inter-related problems of social inequality and declining accessibility. Using STELLA modeling software we investigate the underlying structural relationships between social equity and accessibility in the Detroit region (Gladwin, 2008; Grengs, 2008; Skerlos 2008; Simon, 2008; Wingfield, 2008).
We begin with an overview of social equity and accessibility globally as well as locally in Detroit, and then discuss the iterative process of model formation and testing. Finally we conclude with study insights and recommendations for industry, policy makers as well as general sustainability recommendations.

**Social Equity**

The divide between the rich and poor has been growing, and this inequality in wealth is expected to continue. The wealthiest 25% of the world’s population owns 75% of the world’s total wealth. In terms of growth, the bottom 80% of the U.S. population has experienced less than 1% in income growth, while the wealthiest 20% of the U.S. population has experienced about 3% and those individuals at the very top, such as CEOs, have seen nearly exponential growth ("Five Mega-Trends", 2006).

Fueled by past racial tensions and currently by Michigan’s poor economy, a divide between the rich and poor has led to a highly segregated Detroit. In the Detroit region, poverty is concentrated downtown with 18.8% of the population in the city living at or below the federal poverty guidelines of $10,210 per person a year and an unemployment rate of 8.4% (U.S. Census, 2006; Federal Register, 2007). In contrast, in the neighboring suburbs of Oakland county only 7.8% of the population is living below the federal poverty guidelines, while 40% of the population is considered high-income (earning more than $75,000 per year), and the unemployment rate is 5.8% (U.S. Census, 1999; U.S. Census 2004; U.S. Census 2006).

**Accessibility and Mobility**

Accessibility is a function of mobility, proximity, and connectivity and is concerned with several factors that make reaching opportunities feasible (Grengs, 2005; Grengs, 2008). For example, of
interest for this paper, accessibility indicators related to jobs take into account: “the spatial location of jobs, the spatial location of residences, whether a worker travels by car or bus, the relative travel time required, and the spatial location of other workers competing for a job” (Shen, 1998; Grengs, 2005, pg. 59). Based on this definition, proximity, or the physical arrangement of opportunities is particularly important because it affects travel time and cost. However, mobility is a derived demand driven by proximity and the need to access opportunities (Grengs, 2008).

Therefore, mobility is “principally a means of improving accessibility”, although it is not the only means of improving accessibility (WBCSD, 2001 pg. 1-5). Beginning in the twentieth century, innovations in the automobile and airplane greatly increased personal mobility. With this increased volume of personal travel and goods movement came positive economic and social benefits like greater access to relatives, employees, raw materials, medical attention, and education. However, mobility is becoming increasingly associated with negative consequences such as increased pollution, congestion, greenhouse gas emissions, and accidents (WBCSD, 2001).

**Sustainable Mobility**

For mobility to be sustainable it must improve accessibility with minimal negative environmental, social, and economic consequences. The World Business Council on Sustainable Development has defined sustainable mobility as “the ability to meet the needs of society to move freely, gain access, communicate, trade, and establish relationships without sacrificing other essential human or ecological values, today or in the future” (WBCSD, 2001 pg. 1-2). To a certain extent, what actually constitutes sustainable mobility can differ depending on location (Octopus, 2006; MTE, 2004; WBCSD, 2001).
New Mobility

Recently a transformation in sustainable, integrated, urban transportation has taken shape providing the basis for a New Mobility industry (Zielinski, 2006; MTE and ICF, 2002). Broadly defined, New Mobility is “the next generation of urban transportation systems, services and products. New Mobility innovations span the spectrum of transportation, from moving people, to moving goods, to moving less, (where unnecessary travel or shipping is reduced). New Mobility applications are generally integrated, smart, clean, service-oriented and user-focused. New Mobility brings together services and technologies across diverse sectors” (MTE and ICF, 2002). More information and examples of New Mobility innovations, and New Mobility Hub Networks can be found in Appendix E.

Current Status of Accessibility and Mobility: An Unsustainable Trajectory

Conducted by the World Business Council for Sustainable Development (WBCSD), the Sustainable Mobility Project (SMP) was a comprehensive assessment of the current status and challenges related to global sustainable mobility. The report outlined 12 “indicators” that reflect the most important dimensions of sustainable mobility and provided a review of their status at the end of the twentieth century. For the purposes of this report we will highlight two of these indicators related to accessibility- access to mobility and equity in access- as they have the highest causal connectivity (see Appendix C and D; WBCSD, 2001). Based on the WBCSD’s overall assessment of these indicators, the SMP concluded that, “global society faces a major dilemma. The world’s present mobility trajectory is unsustainable. As the need and demand for mobility continue to grow worldwide, it has become clear that mobility, as we know it today, must change, if it is to become sustainable. Moreover, achieving sustainable mobility by the mid-century will require contributions from all stakeholders” (WBCSD, 2004).
Access to Mobility

In the developed world personal mobility is at its highest levels, while populations in the developing world continue to have much lower levels of mobility (Figures 1 and 2). (In this report “developed world” refers to OECD countries excluding Mexico and Korea). The figures illustrate the levels of annual per capita personal transportation across regions of the world by mode (Figure 1) and by mode share (Figure 2). According to this data, the amount of travel per person and the mode of travel they choose to take vary greatly by region; however, the automobile accounts for at least 50% of the distance traveled in most regions of the world today (WBCSD, 2001).

In contrast to many parts of the developed world, only the wealthy populations in Detroit truly experience high levels of personal mobility. As the motor capital of the world, Detroit is heavily dominated by vehicle travel, and auto ownership is an important determinant of employment accessibility (Shen, 1998). In Detroit 91% of the population commutes by car, with 9% using public transit, and in the neighboring suburbs of Oakland county 98% of the population commutes by car with only 2% using public transit to access jobs (Detroit Area Study, 2001).
Equity in Access

Worldwide access to mobility varies greatly by age, income, and geographic location—with the poor, the elderly, and women often having the most limited access to mobility. Currently only 12% of the world’s population has access to motorized transportation (WBCSD, 2001). In regions globally with GDPs ranging from $500 to $20,000 per capita, travel increases in...
proportion to increases in their income as they gain the means to access faster modes of transport (WBCSD, 2001).

In Detroit, the center of the city is accessibility-deficient with the poor having limited access to mobility (Grengs, 2005). According to Grengs, “the central city contains the region’s neediest transportation constituencies, the place where the greatest share of poor residents reside and the place where the greatest share of carless households reside (Grengs, 2005 pg. 59).”

**Social Equity and Accessibility**

Increasing social inequity is having a detrimental effect on accessibility, particularly for individuals without personal vehicles. Often times these accessibility issues are disproportionately affecting the young, the elderly, the disabled, and the poor (MTE, 2002; Rosenbloom 2004). Due to the inconvenience of travel and higher costs associated with it, these individuals can become increasingly isolated from society. The situation is particularly dire in Detroit as the “well-known economic and racial ‘wall’ that divides Detroit from its neighbours is fortified, due partly to the inability of planners and policy makers to integrate two separate transit systems(Grengs, 2005 pg. 60).”

**Defining the Purpose of the Model**

As discussed in the introduction, accessibility is a primary driver and impediment of sustainable mobility (see also Appendix C and D). Furthermore, access to mobility is highly unequal, often advantaging the wealthy and those with automobiles (Shen, 1998; Grengs, 2005). Our model investigates the underlying structural relationships between social equity and accessibility in the Detroit region (Gladwin, 2008; Grengs, 2008; Skerlos 2008; Simon, 2008; Wingfield, 2008).
We use STELLA modeling software to test the hypothesis that urban flight, and a growing concentration of wealth in the suburbs is leading to an unsustainable decline in accessibility for the low-income population in Detroit. We seek to understand the root causes of the declining accessibility vis a vis commute time and cost to work by car and public transit for high, middle and low income populations in Detroit as well as two suburbs, Farmington in Oakland County and Warren in Macomb County (Gladwin, 2008; Grengs, 2008; Skerlos 2008; Simon, 2008). The time period of interest is 2000 to 2050.

To gain an understanding of the effects of sustainability measures on accessibility, we consider the effects of New Mobility Hub Network time and cost efficiencies, and their impact on accessibility (Gladwin and Zielinski, 2008). To gain an understanding of the effects of public policy on accessibility, we consider policy measures related to government spending on roads and public transit, as well as increasing job opportunities for low-income residents within Detroit, increasing low-income housing in the suburbs, and providing incentives for high-income residents to move back to Detroit, and a shift in urban planning policy and goals prioritizing dense mixed-use development (Gladwin and Zielinski, 2008; Grengs 2005).

**Defining the Model Boundary and Identifying Key Variables**

Key endogenous and exogenous variables as well as sustainability and policy relevant components are identified below. The full model including all variables and associated equations can be found in Appendix A and B.

The primary endogenous variables in the model are accessibility by public transit and car per income level and location; commute time by public transit and car; government spending for roads and public transit; commuters by car and public transit; commuters per income level and
location; effect of government spending for roads and public transit on commute time; commute cost by public transit and car; mode decision to switch modes per income level and location; effect of decision on commuters switching modes; hub network time and cost efficiencies; change in commute time due to hub efficiencies; change in commute time by public transit due to government spending; effect of change in car commuters on commute time; commute cost per mile by car; and commute distance.

The primary exogenous variables in the model are job opportunities per income level and location; number of car and public transit commuters per income level and location; strength of opinion on government spending per income level; normal growth rate of government spending; percent change in government spending on roads and public transit; priority of saving time over money; delay for public transit implementation; delay for road construction; normal rate of increase in cost per mile by car; perceived time different; and perceived cost difference.

In addition the following stocks are identified: commute time by public transit and car; government spending on transportation; commute cost by public transit; commuters by car and public transit; and commute cost by car per mile.

The primary flow components include: the increase in government spending, the change in commute time by public transit, commuters switching mode, and the change in commute cost by car per mile.

The sustainability-relevant components in the model are New Mobility Hub Network time and cost efficiencies. The policy relevant components in the model are government spending for roads and public transit; strength of opinion on government spending; and percent change in government spending on roads and public transit.
Identifying and Describing the Reference Pattern

Reference behavior patterns of interest for this model include: accessibility by income level, commute time by car and public transit, commute cost by car and public transit, and government spending on roads and public transit in Detroit.

Our hypothesized reference pattern for accessibility is declining for the low-income population, but stable or increasing for middle and high income due to their disproportionate access to cars since 1950 (Grengs, 2005; Grengs, 2008; Skerlos, 2008).

Our historical reference patterns suggest increasing commute time by car and public transit (Figure 3), increasing commute cost by car and to a lesser extent also by public transit (Figure 4 and 5), and stagnant government spending on roads and public transit (Figure 6) (U.S. Department of Transportation, 2000; Google Maps, 2008; SMART 2008; U.S. Department of Labor 2007; Macomb County Road Commission, 2004; Mackinac.org, 2006; Detroit News, 2008).
Figure 3. Commute time by car and public transit in Detroit (U.S. Department of Transportation, 2000; Google Maps, 2008; SMART, 2008).

Figure 4. Commute cost by car in Detroit (U.S. Department of Labor, 2007).
Figure 5. Commute cost by public transit in Detroit (SMART, 2008).

Figure 6. Government spending on roads and public transit in Detroit (Macomb County Road Commission, 2004; Mackinac.org, 2006; Detroit News, 2008).
Pinpointing the Basic Mechanisms

Our dynamic hypothesis is that urban flight, and a growing concentration of wealth in the suburbs is leading to an unsustainable decline in accessibility for the low-income population in Detroit. The basic mechanisms are best illustrated in the causal map below (Figure 7). Essentially high-income commuters in Detroit disproportionately influence government priority on spending for transportation. As the wealthy are most reliant on their cars and least reliant on public transit their influence over government spending results in spending on efficiency measures, e.g. roads, rather than social goals, e.g. public transit for those who cannot drive or do not have access to mobility (Grengs, 2005).

Causal Mapping

Figure 7. Causal map of equity of access.
Pinpointing the Dynamic Organizing Principles

The central theme is the cascading affect of urban flight, e.g. as the wealthy population in Detroit becomes wealthier they move farther from the central city of Detroit and this has an affect on accessibility throughout the city. As the high-income population moves to the suburbs, they also take a number of jobs, including service and blue-collar jobs, with them. Currently the greatest job growth is occurring 15 miles or more from downtown Detroit (Grengs, 2005). Due to the sprawling land-use patterns in Detroit’s suburbs and the lacking of regional public transit coordination, the wealthy rely almost entirely upon their car for commuting to work, while the low-income population is forced to suffer through long commute times on public transit. The situation is exacerbated by longer commute times for the low-income population as they follow the job opportunities that are increasingly far away from downtown Detroit. Furthermore government spending is influenced largely by the high-income population who favor spending on roads, thereby shifting governmental priority away from regional collaboration for public transit, and “social goals” for those without access to mobility to efficiency and reducing congestion for suburban commuters (Grengs, 2005).

The system archetype, “success to the successful” is at work within this model. The high-income population has a disproportionate influence on government spending for transportation. As the high-income population is primarily reliant on commuting by car they influence government spending in the direction of roads to improve their accessibility. This simultaneously results in fewer government funds available to be spent on public transit thereby decreasing the accessibility of the low-income population who are the primary users of public transit. To a lesser extent the “shifting the burden” system archetype is also at work within this model. Government spending on roads is a short-term, technological fix to the bigger problem of
increased commute time and declining accessibility, that can only truly be addressed through a systems approach to transportation and land-use planning that includes public transit.

**Understanding the Parameter Values**

Model design methodology

- 3 spatial locations: Wayne (Detroit), Oakland, Macomb
- 3 income levels: Low ($), Mid ($$), High ($$$)
- 4 commute paths: 1 between each of the other locations, and 1 within a single location

**Accessibility by Mode**

Job Opportunities per Income Level and Location: Data from US Census (U.S. Census, 2000). Much of this accessibility calculation derives from a paper by Q. Shen. Therefore, the equations provided below are only representative of more general equations outlined in this work (Shen, 1998).
Total Jobs Supply * Income Level Percentage

<table>
<thead>
<tr>
<th>Location (County)</th>
<th>Wayne</th>
<th>Macomb</th>
<th>Oakland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population - Total</td>
<td>894058</td>
<td>421446</td>
<td>630690</td>
</tr>
<tr>
<td>% Low Income</td>
<td>0.188</td>
<td>0.082</td>
<td>0.078</td>
</tr>
<tr>
<td>% Middle Income</td>
<td>0.59</td>
<td>0.62</td>
<td>0.522</td>
</tr>
<tr>
<td>% High Income</td>
<td>0.222</td>
<td>0.298</td>
<td>0.4</td>
</tr>
<tr>
<td>Unemployment Rate</td>
<td>0.084</td>
<td>0.072</td>
<td>0.058</td>
</tr>
<tr>
<td>Jobs - Private</td>
<td>705771</td>
<td>308750</td>
<td>746068</td>
</tr>
<tr>
<td>Jobs - Government</td>
<td>127874</td>
<td>41202</td>
<td>60912</td>
</tr>
<tr>
<td>Jobs - Low Income</td>
<td>156725</td>
<td>28696</td>
<td>62944</td>
</tr>
<tr>
<td>Jobs - Middle Income</td>
<td>491851</td>
<td>216970</td>
<td>421244</td>
</tr>
<tr>
<td>Jobs - High Income</td>
<td>185069</td>
<td>104286</td>
<td>322792</td>
</tr>
</tbody>
</table>

We constructed a 2 dimensional array to contain job data for 3 locations, at 3 income levels.

<table>
<thead>
<tr>
<th>Location (County)</th>
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</tr>
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<tbody>
<tr>
<td>Low Income</td>
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<tr>
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<td>491851</td>
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<td>421244</td>
</tr>
<tr>
<td>High Income</td>
<td>185069</td>
<td>104286</td>
<td>322792</td>
</tr>
</tbody>
</table>

**Beta**

Friction factor used in as a level of impedance based on distance, cost, or time (Shen, 1998).

0.1

**Supply Potential by Car**

The number of job opportunities for each income level, modified by Car Commute Time and Beta (Shen, 1998).

\[
\text{Job Opportunities per IL and Loc[Low,Dwtn]} \ast \exp(-1\ast\text{Beta}\ast\text{Commute Time by Car[Local]}) + \\
\text{Job Opportunities per IL and Loc[Low,SubA]} \ast \exp(-1\ast\text{Beta}\ast\text{Commute Time by Car[Dwtn AND SubA]}) + \\
\text{Job Opportunities per IL and Loc[Low,SubB]} \ast \exp(-1\ast\text{Beta}\ast\text{Commute Time by Car[Dwtn AND SubB]})
\]

**Demand Potential by Car**

The number of commuters for each income level, modified by Car Commute Time and Beta, as derived in the Shen paper (Shen, 1998).
Commuters per IL and Loc[Low,Dwtn] * EXP(-1*Beta*Commute Time by Car[Local]) +
Commuters per IL and Loc[Low,SubA] * EXP(-1*Beta*Commute Time by Car[Dwtn AND SubA]) +
Commuters per IL and Loc[Low,SubB] * EXP(-1*Beta*Commute Time by Car[Dwtn AND SubB])

Accessibility by Car per Income Level and Location

Ratio of supply and demand for jobs by car for each income level and location.

Supply Potential by Car[Income_Level,Location] / Demand Potential by Car[Income_Level,Location]

Supply Potential by Public Transit

The number of job opportunities for each income level, modified by Public Transit Commute Time and Beta (Shen, 1998).

Job Opportunities per IL and Loc[Low,Dwtn] * EXP(-1*Beta*Commute Time by PT[Local]) +
Job Opportunities per IL and Loc[Low,SubA] * EXP(-1*Beta*Commute Time by PT[Dwtn AND SubA]) +
Job Opportunities per IL and Loc[Low,SubB] * EXP(-1*Beta*Commute Time by PT[Dwtn AND SubB])

Demand Potential by Public Transit

The number of commuters for each income level, modified by Public Transit Commute Time and Beta (Shen, 1998)

Commuters per IL and Loc[Low,Dwtn] * EXP(-1*Beta*Commute Time by PT[Local]) +
Commuters per IL and Loc[Low,SubA] * EXP(-1*Beta*Commute Time by PT[Dwtn AND SubA]) +
Commuters per IL and Loc[Low,SubB] * EXP(-1*Beta*Commute Time by PT[Dwtn AND SubB])

Accessibility by Public Transit per Income Level and Location

Ratio of supply and demand for jobs by Public Transit for each income level and location.

Supply Potential by PT[Income Level,Location] / Demand Potential by PT[Income Level,Location]
Accessibility Index

The accessibility index is adapted from *Accessibility Indicators* of Grengs and Shen in Detroit and Boston (Shen, 1998; Grengs, 2005)

### Accessibility per Income Level

\[
\text{Accessibility by Car per Income Level} = \left( \frac{\text{Accessibility by Car per Income Level}\left[\text{Income Level}\right] \ast \text{ARRAYSUM} (\text{Commuters by Car}\left[\text{Income Level},*\right]) + \text{Accessibility by PT per Income Level}\left[\text{Income Level}\right] \ast \text{ARRAYSUM} (\text{Commuters by PT}\left[\text{Income Level},*\right])}{\text{ARRAYSUM} (\text{Commuters by Car}\left[\text{Income Level},*\right]) + \text{ARRAYSUM} (\text{Commuters by PT}\left[\text{Income Level},*\right])} \right)
\]

### Accessibility by Car per Income Level

\[
\text{IF} (\text{Car Commuters per IL}\left[\text{Income Level}\right] = 0) \\
\text{THEN} \left( \frac{\left( \text{Accessibility by Car per IL and Loc}\left[\text{Income Level},\text{Dwtn}\right] + \text{Accessibility by Car per IL and Loc}\left[\text{Income Level},\text{SubA}\right] + \text{Accessibility by Car per IL and Loc}\left[\text{Income Level},\text{SubB}\right] \right)}{3} \right) \\
\text{ELSE} \left( \frac{\left( \text{Accessibility by Car per IL and Loc}\left[\text{Income Level},\text{Dwtn}\right] \ast \text{Commuters by Car}\left[\text{Income Level, Dwtn}\right] + \text{Accessibility by Car per IL and Loc}\left[\text{Income Level, SubA}\right] \ast \text{Commuters by Car}\left[\text{Income Level, SubA}\right] + \text{Accessibility by Car per IL and Loc}\left[\text{Income Level, SubB}\right] \ast \text{Commuters by Car}\left[\text{Income Level, SubB}\right] \right)}{\text{Car Commuters per IL}\left[\text{Income Level}\right]} \right)
\]

### Accessibility by Car

\[
\text{IF} (\text{Car Commuters} = 0) \\
\text{THEN} \left( \frac{\left( \text{Accessibility by Car per Income Level}\left[\text{Low}\right] + \text{Accessibility by Car per Income Level}\left[\text{Mid}\right] + \text{Accessibility by Car per Income Level}\left[\text{High}\right] \right)}{3} \right) \\
\text{ELSE} \left( \frac{\left( \text{Accessibility by Car per Income Level}\left[\text{Low}\right] \ast \text{Car Commuters per IL}\left[\text{Low}\right] + \text{Accessibility by Car per Income Level}\left[\text{Mid}\right] \ast \text{Car Commuters per IL}\left[\text{Mid}\right] + \text{Accessibility by Car per Income Level}\left[\text{High}\right] \ast \text{Car Commuters per IL}\left[\text{High}\right] \right)}{\text{Car Commuters}} \right)
\]

### Accessibility by PT

\[
\text{IF} (\text{PT Commuters} = 0) \\
\text{THEN} (\text{Accessibility by PT per Income Level}\left[\text{Low}\right] + \\
\text{Accessibility by PT per Income Level}\left[\text{Mid}\right] + \\
\text{Accessibility by PT per Income Level}\left[\text{High}\right] \right)
\]
Accessibility by PT per Income Level[Mid] +
Accessibility by PT per Income Level[High]) / 3)
ELSE((Accessibility by PT per Income Level[Low] * PT Commuters per IL[Low] +
Accessibility by PT per Income Level[Mid] * PT Commuters per IL[Mid] +
Accessibility by PT per Income Level[High] * PT Commuters per IL[High]) /
PT Commuters)

Overall Accessibility

(Accessibility by Car * Car Commuters + Accessibility by PT * PT Commuters) /
(Car Commuters + PT Commuters)

Commuters by Car and Public Transit

We used US Census data to determine the total population for each county, as well as the
percentage within each income bracket (U.S. Census, 2000).

Income Level
Low < $10K
$10K < Mid <75K
High > $75K

Total Population * Percent in Income Bracket

A 2001 Detroit Area Study from the University of Michigan gives us the percent of public transit
riders in each county (Detroit Area Study, 2001).

Total Population * Percent riding Public Transit

We assumed no High income commuters would use public transit and therefore split the public
transit riders equally between Low and Middle income commuters.

Public Transit commuters[Low Income] = Public Transit riders / 2
Public Transit commuters[Mid Income] = Public Transit riders / 2

We can compute the number of people in each county, in each income bracket that are
commuting using car or public transit.

Public Transit Commuters[Low Income]
Public Transit Commuters[Mid Income]
Public Transit Commuters [High Income]

<table>
<thead>
<tr>
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<th>Macomb</th>
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</thead>
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<td>0.62</td>
<td>0.522</td>
</tr>
<tr>
<td>% High Income</td>
<td>0.222</td>
<td>0.298</td>
<td>0.4</td>
</tr>
<tr>
<td>% PT Ridership</td>
<td>0.09</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>% Car Usage</td>
<td>0.91</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Population – Low Income: 168083 34559 49194 people
Population - Middle Income: 527494 261297 329220 people
Population - High Income: 198481 125591 252276 people

PT Ridership: 80465 8429 12614 people
Car Usage: 813593 413017 581496 people

PT Ridership - Low Income: 40233 4215 6307 people
PT Ridership - Middle Income: 40232 4214 6307 people
PT Ridership - High Income: 0 0 0 people

Car Usage – Low Income: 127850 30344 42887 people
Car Usage - Middle Income: 487262 257083 322913 people
Car Usage - High Income: 198481 125591 252276 people

Our two initial stocks, Commuters by Car, and Commuters by Public Transit, are each 2 dimensional arrays.

**Commuters by Car**

<table>
<thead>
<tr>
<th></th>
<th>Location (County)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wayne</td>
</tr>
<tr>
<td>Income Level</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>127850</td>
</tr>
<tr>
<td>Mid</td>
<td>487262</td>
</tr>
<tr>
<td>High</td>
<td>198481</td>
</tr>
</tbody>
</table>

**Commuters by Public Transit**

<table>
<thead>
<tr>
<th></th>
<th>Location (County)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wayne</td>
</tr>
<tr>
<td>Income Level</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>40233</td>
</tr>
<tr>
<td>Mid</td>
<td>40232</td>
</tr>
<tr>
<td>High</td>
<td>0</td>
</tr>
</tbody>
</table>

**Commute Cost by Car and Public Transit**

Commute cost is calculated for each of the 4 commute paths. See figure above. An array with 4 elements was created to hold the data for each commute path.
**Spatial Separation**

Spatial Separation is the geographic separation between the city and suburbs. This separation is then denoted by a measure of time, money, or distance.

**Commute Cost per Mile by Car**

Based on automobile reimbursement rates, which take into consideration all costs of driving. Data from the Department of Labor (Department of Labor, 2008).

\[ \$0.485 \]

**Business Days per Year**

Assumed by authors.

\[ 260 = 5 \text{ days/week} \times 52 \text{ weeks/year} \]

**Daily Commute**

Round trip miles calculated for each of the 4 commute paths from Google Maps.

<table>
<thead>
<tr>
<th>Commute Time</th>
<th>Dtwn – SubA</th>
<th>Dtwn – SubB</th>
<th>SubA – SubB</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35.4</td>
<td>50.5</td>
<td>47.4</td>
<td>30</td>
</tr>
</tbody>
</table>

**Commute Cost by Car**

Daily Commute \times Business Days per Year \times Commute Cost per Mile by Car

**Change in Commute Cost per Mile by Car**

The cost adjusted by a normal increase. We calculated the trend for the previous 10 years (Department of Labor, 2008).

Normal Rate of Increase in Cost per Mile by Car \times Commute Cost per Mile by Car

**Commute Cost by Public Transit**

A bus pass costs $533.39/year. SMART data (SMART, 2008).
$533.39

**Normal Rate of Increase in Public Transit Fare**

SMART data shows no increase in fare (SMART, 2008). Assumption by authors.

0.023

**Change in Commute Cost by Public Transit**

\[
\text{Normal Rate of Increase in PT Fare} \times \text{Commute Cost by PT} - \text{Hub Network Cost Efficiencies} \times \text{Commute Cost by PT}
\]

**Hub Network Cost Efficiencies**

A combination of assumptions by authors and previous mobility models (McMurtry and White, 2008).

**Graphical function**

**Commute Time by Car**

Commute time is calculated for each of the 4 commute paths. See figure above. An array with 4 elements was created to hold the data for each commute path.

**Spatial Separation**

Spatial Separation is the geographic separation between the city and suburbs. This separation is then denoted by a measure of time, money, or distance.

**Initial Congestion Index**

Taken from the report by the Texas Transportation Institute (TTI, 2008).

1.29
**Free Flow Travel Time by Car & Initial Commute Time by Car**

Free Flow Travel Time is defined as a route with no congestion. This is calculated from Google Maps (Google Maps, 2008).

\[
\text{Initial Congestion Index} \times \text{Free Flow Travel Time by Car}
\]

<table>
<thead>
<tr>
<th></th>
<th>Dtwn – SubA</th>
<th>Dtwn – SubB</th>
<th>SubA – SubB</th>
<th>Local</th>
</tr>
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<tbody>
<tr>
<td>Commute Time</td>
<td>35.4</td>
<td>50.5</td>
<td>47.4</td>
<td>30</td>
</tr>
<tr>
<td>Free Flow Time</td>
<td>30.96</td>
<td>45.15</td>
<td>39.99</td>
<td>25.8</td>
</tr>
</tbody>
</table>

**Total Effect on Car Commute Time**

A combination of government spending on roads and a change in the number of commuters using the roads.

\[
\text{Delayed Effect of Spending for Roads on Commute Time} + \text{Effect of Change in Car Commuters on Commute Time}
\]

**Delay for Road Construction**

Assumed by the authors.

2 years

**Discrepancy in Car Travel Time**

The gap between ideal (free flow) and current conditions.

\[
\text{Commute Time by Car} - \text{Free Flow Travel Time by Car}
\]

**Change in Commute Time by Car**

The effect is multiplied by either the current commute time, or the gap.

\[
\text{IF} (\text{Total Effect on Car Commute Time} < 0) \\
\text{THEN} (\text{Total Effect on Car Commute Time} \times \text{Discrepancy in Car Travel Time}) \\
\text{ELSE} (\text{Total Effect on Car Commute Time} \times \text{Commute Time by Car})
\]
Commute Time by Public Transit

Commute time is calculated for each of the 4 commute paths. See figure above. An array with 4 elements was created to hold the data for each commute path.

_initial Commute Time by Public Transit_

Calculated using Google Maps and SMART route data (Google Maps, 2008).

<table>
<thead>
<tr>
<th>Commute Time</th>
<th>Dtwn – SubA</th>
<th>Dtwn – SubB</th>
<th>SubA – SubB</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>44</td>
<td>122</td>
<td>95</td>
<td>40</td>
</tr>
</tbody>
</table>

_Total Effect on Public Transit Commute Time_

A combination of Government spending on public transit and Hub Network Time Efficiencies.

_Delayed Effect of Spending for PT on Commute Time – Hub Network Time Efficiencies_

_Delay for Public Transit implementation_

Assumed by the authors.

1 year

_Hub Network Time Efficiencies_

A combination of assumptions by the authors and previous mobility models (McMurtry and White, 2008).

_Graphical function_

_Discrepancy in Public Transit Travel Time_

The gap between ideal (free flow) and current conditions.

Commute Time by PT – Free Flow Travel Time by Car
Change in Commute Time by Public Transit

The effect is multiplied by either the current commute time, or the gap.

\[
\text{IF(Total Effect on PT Commute Time} < 0) \text{ THEN(Total Effect on PT Commute Time} \times \\
\text{Discrepancy in PT Travel Time) ELSE(Total Effect on PT Commute Time} \times \\
\text{Commute Time by PT)}
\]

Decision to Switch Transit Mode

The decision to switch modes is extremely personal for each individual, and in real-world situations would usually include numerous inputs. For our model, we chose to focus on 2 elements common to all commuters; time and cost. When a combination of time and cost reaches a threshold, a commuter decides to switch commuting modes. We also included the income level of the commuter, recognizing the differences in weighting time and cost for wealthy and poor.

Time Difference

Calculate the difference in commute time between car and public transit.

\[
\text{ABS(Commute Time by Car[Spatial_Separation]} – \text{Commute Time by PT[Spatial_Separation])}
\]

Time Percent

Calculate the percent difference in commute time between car and public transit.

\[
\text{IF(Commute Time by Car[Spatial_Separation]} > \text{Commute Time by PT[Spatial_Separation])}
\]

\[
\text{THEN((Commute Time by Car[Spatial_Separation]} – \text{Commute Time by PT[Spatial_Separation])} / \text{Commute Time by Car[Spatial_Separation])}
\]

\[
\text{ELSE ((Commute Time by Car[Spatial_Separation]} – \text{Commute Time by PT[Spatial_Separation])} / \text{Commute Time by PT[Spatial_Separation])}
\]

Perceived Time Difference

Perception of how much time you're using to commute by a particular mode. A positive number suggests that on average a commuter would perceive public transit to be the better option. A
negative number indicates that the average commuter would perceive using a car as the better option.

\[ \text{Time Percent}[\text{Spatial} \_ \text{Separation}] \times \text{Time Difference}[\text{Spatial} \_ \text{Separation}] \]

### Cost Difference

Calculate the difference in commute cost between car and public transit.

\[ \text{ABS}((\text{Commute Cost by Car}[\text{Spatial} \_ \text{Separation}] - \text{Commute Cost by PT}) \]

### Cost Percent

Calculate the percent difference in commute cost between car and public transit.

\[ \begin{align*} 
\text{IF}(&\text{Commute Cost by Car}[\text{Spatial} \_ \text{Separation}] > \text{Commute Cost by PT}) \\
\text{THEN}(&((\text{Commute Cost by Car}[\text{Spatial} \_ \text{Separation}] - \text{Commute Cost by PT}) / \text{Commute Cost by Car}[\text{Spatial} \_ \text{Separation}]) \\
\text{ELSE}(&((\text{Commute Cost by Car}[\text{Spatial} \_ \text{Separation}] - \text{Commute Cost by PT}) / \text{Commute Cost by PT}) \end{align*} \]

### Perceived Cost Difference

Perception of how much money you're paying to commute by a particular mode. A positive number suggests that on average a commuter would perceive public transit to be the better option. A negative number indicates that the average commuter would perceive using a car as the better option.

\[ \text{Cost Percent}[\text{Spatial} \_ \text{Separation}] \times \text{Cost Difference}[\text{Spatial} \_ \text{Separation}] \]

### Max Expected Time

Assumed by authors.

100 min
Scaling of Mode Decision for Time per Income Level

Assumed by authors. Increasing the scaling will result in a linear increase in mode switching for a given Perceived Time Difference. Increasing the scaling will result in more people deciding that Time is an important factor in their decision to switch Transit Mode.

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time Exponent per Income Level

Assumed by authors. Time Exponent variables change the polynomial exponent. The exponent must be an odd value >=3. A larger odd number will delay when people decide it is important to switch Transit Modes, but once they begin to switch, a greater number will decide to do so. With high (5, 7) values, you might begin to see oscillations.

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time Based Mode Decision per Income Level and Spatial Separation

Scaling of Mode Decision for Time per IL[Income_Level] * (Perceived Time Difference[Spatial_Separation] / Max Expected Time)^[Time Exponent per IL[Income_Level]]
Max Expected Cost

Assumed by the authors.

$10,000

Scaling of Mode Decision for Cost per Income Level

Assumed by authors. Increasing the scaling will result in a linear increase in mode switching for a given Perceived Cost Difference. Increasing the scaling will result in more people deciding that Cost is an important factor in their decision to switch Transit Mode.

<table>
<thead>
<tr>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Cost Exponent per Income Level

Assumed by authors. Cost Exponent variables change the polynomial exponent. The exponent must be an odd value $\geq 3$. A larger odd number will delay when people decide it is important to
switch Transit Modes, but once they begin to switch, a greater number will decide to do so. With high (5, 7) values, you might begin to see oscillations.

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**Cost**

![Graph showing the relationship between perceived time difference and percent switching mode](image)

Figure 9. Cost based mode decision.

**Mode Decision per Income Level and Spatial Separation**

A weighted indicator of a desire to switch modes based on different factors. For example, a low income person cares more about money than time, while a high income person cares more about time than money. Based on this system, if the Mode Decision > 0, then the average commuter desires to travel by public transit. Conversely, if the Mode Decision < 0, then traveling by car is more desirable.

\[
\text{Time Based Mode Decision per IL and Spatial Sep[Income\_Level, Spatial\_Separation]} + \text{Cost Based Mode Decision per IL and Spatial Sep[Income\_Level, Spatial\_Separation]} \]
**Mode Decision per Income Level and Location**

Calculated for each Income Level and each commute path.

\[
\text{Mode Decision per IL and Spatial Sep}[\text{Low,Dwtn}\_\text{AND}\_\text{SubA}] + \\
\text{Mode Decision per IL and Spatial Sep}[\text{Low,Dwtn}\_\text{AND}\_\text{SubB}] + \\
\text{Mode Decision per IL and Spatial Sep}[\text{Low,Local}]) / 3
\]

**Strength of Opinion**

**Strength of Opinion in Government per Income Level**

How much voice do Low, Middle, and High Income people have in the way the government spends money on roads and public transit projects. Sum must always equal 1.

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Weighted Fraction of Government Spending for Roads per Income Level**

\[
\text{Strength of Opinion in Govt per IL[Income\_Level]} \times \\
\text{Desired Fraction of Govt Spending for Roads per IL[Income\_Level]}
\]

**Fraction of Government Spending for Roads**

\[
\text{ARRAYSUM(Weighted Fraction of Govt Spending for Roads per IL[*])}
\]

**Government Spending**

**Government Spending on Transportation**

- **Government Spending Growth Rate**: 0.004 fraction/yr, Macomb County Road Commission
- **Government Spending on PT**: 272 $M, Mackinac.org
- **Government Spending on Roads**: 1300 $M, Detroit News
- **% Govt Spending on Highways**: 0.75 % spending, Macomb County Road Commission
- **% Govt Spending on Arterial Roads**: 0.25 % spending, Macomb County Road Commission

**Normal Growth Rate of Government Spending**

The normal growth rate of government spending is based on Macomb County Road Commission estimate (Macomb County Road Commission, 2004).
Effect of Government Spending

Government Spending for Roads
Uses the ‘Strength of Opinion’ value.

Fraction of Govt Spending for Roads * Govt Spending on Transportation

Government Spending for Roads from Previous Year
Based on government spending for roads with a delay for construction.

DELAY(Govt Spending for Roads, 1)

Percent Change in Spending for Roads
Percentage should be bound between -1 and 1.

IF(Govt Spending for Roads > Govt Spending for Roads for Previous Year)
THEN(((Govt Spending for Roads – Govt Spending for Roads for Previous Year) / Govt Spending for Roads)
ELSE(((Govt Spending for Roads – Govt Spending for Roads for Previous Year) / Govt Spending for Roads for Previous Year)

Government Spending for Public Transit

Govt Spending on Transportation – Govt Spending for Roads

Government Spending for Public Transit from Previous Year
Based on government spending for public transit with a delay for implementation.

DELAY(Govt Spending for PT, 1)

Percent Change in Spending for Roads
Percentage should be bound between -1 and 1.

IF(Govt Spending for PT > Govt Spending for PT for Previous Year)
THEN(((Govt Spending for PT – Govt Spending for PT for Previous Year) /
Govt Spending for PT)
ELSE((Govt Spending for PT – Govt Spending for PT for Previous Year) /
Govt Spending for PT for Previous Year)

**Effect of Spending for Roads on Commute Time**

Assumed by the authors.

Graphical function

**Effect of Spending for Public Transit on Commute Time**

Assumed by the authors.

Graphical function

**Testing the Dynamic Hypothesis**

The model reinforces our assumptions and accurately reflects our dynamic hypothesis. Accessibility for all income levels is stagnant for the reference period, and then increases in later years (Figure 10).

Figure 10. Accessibility overall, by car and public transit.
Commute time for public transit increases at first, then decreases, a direct effect of government spending. Commute time for cars also decreases (Figures 11 and 12). Commute cost by car and public transit both increase over the reference period (Figures 13 and 14). One of the basic mechanisms of our model is how government chooses to spend money on transportation. Our model reflects our expectations, showing government spending for roads is flat, or slightly increasing, then declines. Spending for public transit is flat, and then increases. The overall trend shows an increase in spending (Figure 15).

Figure 11. Commuter time by car and location.
Figure 12. Commute time by public transit and location.

Figure 13. Commute cost by car and location.
Figure 14. Commute cost by public transit.

Figure 15. Government spending on transportation, roads, and public transit including previous year.
Adjustments

Initially, we used an accessibility calculation for car commuters and public transit commuters that did not reflect their income level. Later, we implemented the multi-dimensional arrays to reflect commuters from different income levels, each commuting between 3 different locations. We also realized that the decision commuters make to switch modes of transportation was central to the model. A complex decision tree, including a 3rd order polynomial, was constructed to give weight to the time and cost factors that affect each income level at each location.

Without limits, our model showed all commuters eventually moving to public transit, leaving roads empty. Based on public transit ridership levels in Manhattan, we decided to artificially cap the maximum amount of public transit riders; 80% for high income, 90% for middle income, 100% for low income population. In future versions, we may want to include more than 3 locations and commute paths. We could consider the cost-driver effects of oil shortages or a carbon tax. We may include policy drivers such as a repeal of government subsidies for public transit, or land use and urban planning policies that favor dense development.

Sensitivity Testing

Our model is most sensitive to the commuter's decision to switch modes of transportation. This is reflected in the decision tree on page 7 of the model (see Appendix A). The decision to switch modes is extremely personal for each individual, and in real-world situations would usually include numerous inputs. For our model, we chose to focus on 2 elements common to all commuters; time and cost. When a combination of time and cost reaches a threshold, a commuter decides to switch commuting modes (Figures 16 and 17). We also included the income level of the commuter, recognizing the differences in weighting time and cost for wealthy and poor.
Figure 16. Changing the exponent flattens the curves.

Figure 17. Changing the range shrinks the curves. Smaller value decreases weight of perceived time difference.
Testing the Impact of Policy Changes

We tested the impacts of Hub Network time and cost efficiencies, as well as 4 policy scenarios. Hub Network time and cost efficiencies can be easily turned on or off in our model. Once implemented, Hub Networks accelerate the changes in time and cost for public transit as expected increasing public transit commuters and low-income accessibility.

Scenario 1: Increasing Low Income Housing in the Suburbs

Overall access remained constant. Suburban accessibility decreased, while downtown accessibility increased, effectively canceling each other.

Scenario 2: Increasing Jobs Downtown for Low Income Commuters

As expected, accessibility for low income commuters in downtown increased.

Scenario 3: Increasing High Income Housing in Downtown

Increasing the high income housing in downtown increases the number of car commuters in downtown, decreases the accessibility for high income commuters, but has little effect on low income commuters in the absence of job creation.

Scenario 4: Implementing an Urban Planning Policy to Lower Commute Time

When implementing urban planning measures such as New Urban, dense development, with a shorter local commute (we assumed a decrease in time from 25 minutes to 10 minutes round trip), accessibility remains the same. This is due to the fact that all income levels are affected simultaneously. Future models may feature individual local commute times.
Study Insights

Our model illustrates stagnating levels of accessibility to jobs for low-income Detroiter both by car and public transit, with increasing associated commute time and cost that is unsustainable. Unlike many cities, there is not a locational advantage related to employment accessibility for low-income workers to live in downtown Detroit. In contrast to other findings, employment decentralization in Detroit has led to an “overall spatial disadvantage for low-wage workers remaining in the urban center (Shen, 1998 pg. 358)”. The underlying causes of this problem are a high concentration of wealthy people in the suburbs of Detroit with disproportionate influence over government spending on transit and roads. As the wealthy are most reliant on their cars and least reliant on public transit their influence over government spending results in spending on efficiency measures, e.g. roads, rather than social goals, e.g. public transit for those who cannot drive or do not have access to mobility (Grengs, 2005). Therefore auto ownership is an important determinant in employment accessibility. However, the model does suggest that increasing commute time and cost by car in the future, particularly when accompanied by Hub Network time and cost efficiencies, increase public transit ridership and accessibility for the low-income population.

Industry and public policy roles and impacts, as well as sustainability recommendations are outlined below with an aim at addressing the unsustainable nature of the study insights.

Industry Roles and Impacts

In the short term employers can act to improve the accessibility of low-income residents in Detroit by providing them with a travel stipend to reduce the pain of the increasing commute cost.
Employers can also support local and regional efforts to improve public transit and New Mobility Hub Networks. Benefits of public transit and hubs for businesses include an increased labor pool, revitalization of business districts, and a potential increase in the tax base in communities with transit (Grengs, 2005; Whit, 1982; Yago, 1984; Adler, 1987; Cevero, 1994, Vuchic, 1999).

Longer term, businesses can improve accessibility in Detroit by locating their operations in the city rather than the suburbs and supporting development of housing in the suburbs for low-income families. Both measures would allow the low-income population to live closer to their place of work, thereby reducing their commute time and cost.

**Policy Roles and Impacts**

Regional collaboration to reduce commute time by public transit is an essential policy measure to improve accessibility in the short term.

Longer term, the issue can only be addressed with an emphasis by policy makers on “social goals” and spending that increases accessibility via public transit, particularly for low-income Detroiters. Supporting transit has many social and economic benefits. Commonly cited economic benefits include job creation, as well as “improved mobility, reduced road congestion and travel time, linkages among different transportation modes, and reduced household transportation costs (Grengs, 2005; Pucher and Lefevre, 1996; Vuchic, 1999).” A Cambridge Systematics study found that “314 jobs are created for every $10 million of transit capital investment, that 570 jobs are created for every $10 million of spending on operating transit services (Grengs, 2005; Cambridge Systematics, 1999). “ Job creation is particularly important to Detroit at this point, as unemployment continues to rise, and an increasing number of people are living below the
poverty line. Social benefits are also widely cited and include enhancing livability, increasing mobility for people without cars as well as the disabled and elderly, and reducing congestion (Vuchic, 1999; Fielding, 1987; Weiner, 1999; Rosenbloom, 2004; Grengs, 2005).

Another role for policy makers is to encourage and support New Mobility Hub Network industry development in Detroit and the suburbs. This would have many of the same social and economic benefits of improving public transit, and would complement the public transit improvements.

Finally, policy makers can promote development of low-income housing in the suburbs as well as incentives that encourage high-income residents to live in Detroit. These measures decrease the distance that low-income residents need to travel to work, and increase the number of jobs in the city and their accessibility to the large majority of low-income residents living there respectively.

**Sustainability Recommendations**

Focusing on access to mobility and equity in access will be important leverage points in achieving sustainable mobility in Detroit due to their high total connectivity with the other variables (see Appendix C and D). Recommendations to increase access to mobility and equity in access include preservation and expansion of the public transit system, encouraging dense urban land use, and adapting the transport system to offer greater timing and routing flexibility by drawing upon emerging vehicle and information technologies (WBCSD, 2004). In both cases, New Mobility industry type solutions as discussed above provide some of the greatest opportunities for increasing access to mobility in a sustainable manner (Zielinski, 2006). As seen in the model new mobility hub time and cost efficiencies accelerate an increasing accessibility by public transit for all residents.
**Study Limitations and Future Modeling Recommendations**

Primary study limitations include a lack of inclusion of some important social factors such as racial discrimination, and the difficulties in using STELLA to examine spatial interactions among different locations over time.

In order to enhance the quality of the modeling output we would recommend several improvements. First we would argue that all assumptions and data in the model should be verified and questioned to ensure their rigor.

As mentioned above, we would also suggest adding variables to capture the impact of a carbon tax on commute cost, modal diversity, new urbanism type land-use planning, and an oil shortage. We would also recommend adding additional locations to the model, e.g. extending beyond two suburbs. While this would add infinite complexity to the model it would provide greater ability to model the underlying structure of the system. We would also like to model more sustainability and policy recommendations as well as include an active industry role.
Appendix A: STELLA Model

Accessibility calculation based on the supply of jobs, the demand for jobs by commuters, and the commute time.
Accessibility Ratio = Low (Middle) Income / High Income Accessibility
Although we know the total number of people switching to cars/year, we don't know which spatial link they took.

In other words, commute time is forced to increase/decrease together for all links.
Effect of Decision on Commuters Switching Modes

Mode Decision per LL and Loc

Max Expected Time

Scaling of Mode Decision per LL

Time Based Mode Decision per LL and Spatial Sep

Time Exponent per LL

Perceived Time Difference

Time Difference

Time Patient

Commute Time by Car

Cost Based Mode Decision per LL and Spatial Sep

Cost Exponent per LL

Perceived Cost Difference

Cost Difference

Cost Patient

Commute Cost by PT

Commute Cost by Car
Strength of HI + Strength of MI + Strength LI = 1 always!

When changing the 'Mode Decision Variables'...
...DON'T play with the 'Cost/Time Exponent' variables first
...Play with Scaling first

...Increasing the scaling will result in a linear increase in mode switching for a given Perceived Time/Cost Difference.
...'Cost/Time Exponent' variables change the polynomial exponent. These values should only be ODD. Larger odd number will delay switching until conditions worsen.
Play with the "Effect of Spending for Roads/PT on Commute Time" b/c they have a large effect on the decision to switch modes.

Govt spending based on collective needs of people (independent of income level or location), so not arrays.
Appendix B: STELLA Equations

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{Low, Dwn}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{Low, Dwn}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{Low, Dwn}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{Low, Dwn}] = 127850 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{Low, SubA}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{Low, SubA}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{Low, SubA}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{Low, SubA}] = 30344 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{Low, SubB}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{Low, SubB}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{Low, SubB}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{Low, SubB}] = 42887 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{Mid, Dwn}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{Mid, Dwn}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{Mid, Dwn}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{Mid, Dwn}] = 487262 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{Mid, SubA}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{Mid, SubA}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{Mid, SubA}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{Mid, SubA}] = 257083 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{Mid, SubB}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{Mid, SubB}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{Mid, SubB}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{Mid, SubB}] = 322913 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{High, Dwn}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{High, Dwn}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{High, Dwn}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{High, Dwn}] = 198481 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{High, SubA}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{High, SubA}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{High, SubA}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{High, SubA}] = 125591 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\[
\text{Commuters}\_\text{by}\_\text{Car}[\text{High, SubB}](t) = \text{Commuters}\_\text{by}\_\text{Car}[\text{High, SubB}](t - \ dt) + \left(\text{Commuters}\_\text{Switching}\_\text{Mode}[\text{High, SubB}] \times \ dt\right) \\
\text{INIT Commuters}\_\text{by}\_\text{Car}[\text{High, SubB}] = 252276 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ (\text{people})
\]

\text{OUTFLOWS:}
\[ \text{Commuters\_Switching\_Mode}(\text{Income\_Level}, \text{Location}) = \]
\[ \begin{align*}
\text{IF} (\text{Effect\_of\_Decision\_on\_Commuters\_Switching\_Modes}(\text{Income\_Level}, \text{Location}) > 0) \quad & \text{THEN} \\
\text{Effect\_of\_Decision\_on\_Commuters\_Switching\_Modes}(\text{Income\_Level}, \text{Location}) \times \\
\text{Remaining\_Car\_Commuters\_Willing\_to\_Switch\_Mode}(\text{Income\_Level}, \text{Location}) \quad & \\
\text{ELSE} & \\
\text{Effect\_of\_Decision\_on\_Commuters\_Switching\_Modes}(\text{Income\_Level}, \text{Location}) \times \\
\text{Commuters\_by\_PT}(\text{Income\_Level}, \text{Location})
\end{align*} \]

\[ \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{Low}, \text{Dwtn})(t) = \text{Commuters\_by\_PT}(\text{Low}, \text{Dwtn})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{Low}, \text{Dwtn})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{Low}, \text{Dwtn}) = 40233 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{Low}, \text{SubA})(t) = \text{Commuters\_by\_PT}(\text{Low}, \text{SubA})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{Low}, \text{SubA})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{Low}, \text{SubA}) = 4215 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{Low}, \text{SubB})(t) = \text{Commuters\_by\_PT}(\text{Low}, \text{SubB})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{Low}, \text{SubB})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{Low}, \text{SubB}) = 6307 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{Mid}, \text{Dwtn})(t) = \text{Commuters\_by\_PT}(\text{Mid}, \text{Dwtn})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{Mid}, \text{Dwtn})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{Mid}, \text{Dwtn}) = 40232 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{Mid}, \text{SubA})(t) = \text{Commuters\_by\_PT}(\text{Mid}, \text{SubA})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{Mid}, \text{SubA})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{Mid}, \text{SubA}) = 4214 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{Mid}, \text{SubB})(t) = \text{Commuters\_by\_PT}(\text{Mid}, \text{SubB})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{Mid}, \text{SubB})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{Mid}, \text{SubB}) = 6307 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{High}, \text{Dwtn})(t) = \text{Commuters\_by\_PT}(\text{High}, \text{Dwtn})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{High}, \text{Dwtn})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{High}, \text{Dwtn}) = 0 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{High}, \text{SubA})(t) = \text{Commuters\_by\_PT}(\text{High}, \text{SubA})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{High}, \text{SubA})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{High}, \text{SubA}) = 0 \{ \text{people} \} \]

\[ \text{Commuters\_by\_PT}(\text{High}, \text{SubB})(t) = \text{Commuters\_by\_PT}(\text{High}, \text{SubB})(t - dt) + \\
(\text{Commuters\_Switching\_Mode}(\text{High}, \text{SubB})) \times dt \\
\text{INIT} \text{Commuters\_by\_PT}(\text{High}, \text{SubB}) = 0 \{ \text{people} \} \]

\[ \text{INFLOWS:} \]
\begin{align*}
\text{Commuters Switching Mode}[\text{Income Level}, \text{Location}] &= \\
&\text{IF(Effect of Decision on Commuters Switching Modes}[\text{Income Level}, \text{Location}] > 0) \\
&\text{THEN(} \\
&\text{Effect of Decision on Commuters Switching Modes}[\text{Income Level}, \text{Location}] \times \\
&\text{Remaining Car Commuters Willing to Switch Mode}[\text{Income Level}, \text{Location}] \\
&\text{ELSE(} \\
&\text{Effect of Decision on Commuters Switching Modes}[\text{Income Level}, \text{Location}] \times \\
&\text{Commuters by PT}[\text{Income Level}, \text{Location}] \\
&\text{)} \\
&\text{people}
\end{align*}

\begin{align*}
\text{Commutation Cost by PT}(t) &= \text{Commutation Cost by PT}(t - dt) + (\text{Change in Commute Cost by PT}) \times dt \\
\text{INIT Commute Cost by PT} &= 533.39 \text{ ($/year)} \\
\text{INFLUENCES:} \\
&\text{Commutation Cost by Car}(t) = \text{Commutation Cost by Car}(t - dt) + \\
&(\text{Change in Commute Cost by Car per Mile}) \times dt \\
\text{INIT Commute Cost by Car} &= 0.485 \text{ ($/mile)} \\
\text{INFLUENCES:} \\
&\text{Commutation Time by Car}[\text{Spatial Separation}](t) = \text{Commutation Time by Car}[\text{Spatial Separation}](t - dt) + \\
&(\text{Change in Commute Time by Car}[\text{Spatial Separation}]) \times dt \\
\text{INIT Commute Time by Car}[\text{Spatial Separation}] &= \text{Initial Commute Time by Car}[\text{Spatial Separation}] \text{ (min)} \\
\text{INFLUENCES:} \\
&\text{Commutation Time by PT}[\text{Dwtn AND SubA}](t) = \text{Commutation Time by PT}[\text{Dwtn AND SubA}](t - dt) + \\
&(\text{Change in Commute Time by PT}[\text{Dwtn AND SubA}]) \times dt \\
\text{INIT Commute Time by PT}[\text{Dwtn AND SubA}] &= 44 \text{ (min)} \\
\text{Commutation Time by PT}[\text{Dwtn AND SubB}](t) &= \text{Commutation Time by PT}[\text{Dwtn AND SubB}](t - dt) + \\
&(\text{Change in Commute Time by PT}[\text{Dwtn AND SubB}]) \times dt \\
\text{INIT Commute Time by PT}[\text{Dwtn AND SubB}] &= 122 \text{ (min)} \\
\text{Commutation Time by PT}[\text{SubA AND SubB}](t) &= \text{Commutation Time by PT}[\text{SubA AND SubB}](t - dt) + \\
&(\text{Change in Commute Time by PT}[\text{SubA AND SubB}]) \times dt \\
\text{INIT Commute Time by PT}[\text{SubA AND SubB}] &= 95 \text{ (min)}
\end{align*}
\[
\text{Commuter Time by PT}(t) = \text{Commuter Time by PT}(t - dt) + \left( \text{Change in Commute Time by PT}(t) \right) \cdot dt
\]
\[
\text{INIT Commuter Time by PT}(\text{Local}) = 40 \text{ (min)}
\]
\[
\text{INFLOWS:}
\]
\[
\text{\textit{Change in Commute Time by PT}}(\text{Spatial Separation}) = \left\{ \begin{array}{ll}
\text{IF} & (\text{Total Effect on PT Commute Time} < 0) \\
\text{THEN} & (\text{Total Effect on PT Commute Time} \cdot \text{Discrepancy in PT Travel Time}(\text{Spatial Separation})) \\
\text{ELSE} & (\text{Total Effect on PT Commute Time} \cdot \text{Commuter Time by PT}(\text{Spatial Separation})) \\
\end{array} \right.
\]
\[
\text{(min)}
\]
\[
\text{Govt Spending on Transportation}(t) = \text{Govt Spending on Transportation}(t - dt) + \left( \text{Increase in Govt Spending} \right) \cdot dt
\]
\[
\text{INIT Govt Spending on Transportation} = 1247e6 \text{ ($)}
\]
\[
\text{INFLOWS:}
\]
\[
\text{Increase in Govt Spending} = \text{Normal Growth Rate of Govt Spending} \cdot \text{Govt Spending on Transportation} \text{ ($)}
\]
\[
\text{($)}
\]
\[
\text{Accessibility by Car} = \left\{ \begin{array}{ll}
\text{IF} & (\text{Car Commuters} = 0) \\
\text{THEN} & \\
& (\text{Accessibility by Car per Income Level}(\text{Low}) + \text{Accessibility by Car per Income Level}(\text{Mid}) + \text{Accessibility by Car per Income Level}(\text{High})) / 3 \\
\text{ELSE} & \\
& (\text{Accessibility by Car per Income Level}(\text{Low}) \cdot \text{Car Commuters per IL}(\text{Low}) + \text{Accessibility by Car per Income Level}(\text{Mid}) \cdot \text{Car Commuters per IL}(\text{Mid}) + \text{Accessibility by Car per Income Level}(\text{High}) \cdot \text{Car Commuters per IL}(\text{High})) / \text{Car Commuters} \\
\end{array} \right.
\]
\[
\text{($)}
\]
\[
\text{Accessibility by Car per IL and Loc}[\text{Income Level}, \text{Location}] = \text{Supply Potential by Car}[\text{Income Level}, \text{Location}] / \text{Demand Potential by Car}[\text{Income Level}, \text{Location}]
\]
\[
\text{($)}
\]
\[
\text{Accessibility by Car per Income Level}[\text{Income Level}] = \left\{ \begin{array}{ll}
\text{IF} & (\text{Car Commuters per IL}(\text{Income Level}) = 0) \\
\text{THEN} & \\
& (\text{Accessibility by Car per IL and Loc}[\text{Income Level}, \text{Dwtn}) + \text{Accessibility by Car per IL and Loc}[\text{Income Level}, \text{SubA}) + \text{Accessibility by Car per IL and Loc}[\text{Income Level, SubB}) / 3 \\
\text{ELSE} & \\
& (\text{Accessibility by Car per IL and Loc}[\text{Income Level, Dwtn}) \cdot \text{Car Commuters by Car}[\text{Income Level, Dwtn}) + \text{Accessibility by Car per IL and Loc}[\text{Income Level, SubA}) \cdot \text{Car Commuters by Car}[\text{Income Level, SubA}) + \text{Accessibility by Car per IL and Loc}[\text{Income Level, SubB}) \cdot \text{Car Commuters by Car}[\text{Income Level, SubB}) / \text{Car Commuters per IL}[\text{Income Level}]
\end{array} \right.
\]
\[
\text{($)}
\]
Accessibility_by_PT = IF(PCT_Commuters = 0)
    THEN (Accessibility_by_PT_per_Income_Level[Low] +
            Accessibility_by_PT_per_Income_Level[Mid] +
            Accessibility_by_PT_per_Income_Level[High]) / 3
    ELSE (Accessibility_by_PT_per_Income_Level[Low] * PCT_Commuters_per_IL[Low] +
            Accessibility_by_PT_per_Income_Level[Mid] * PCT_Commuters_per_IL[Mid] +
            Accessibility_by_PT_per_Income_Level[High] * PCT_Commuters_per_IL[High]) / PCT_Commuters
    {dimensionless}

Accessibility_by_PT_per_IL_and_Loc[Income_Level, Location] =
    Supply_Potential_by_PT[Income_Level, Location] / Demand_Potential_by_PT[Income_Level, Location]
{dimensionless}

Accessibility_by_PT_per_Income_Level[Income_Level] = IF(PCT_Commuters_per_IL[Income_Level] = 0)
    THEN (Accessibility_by_PT_per_IL_and_Loc[Income_Level, Dtwnt] +
            Accessibility_by_PT_per_IL_and_Loc[Income_Level, SubA] +
            Accessibility_by_PT_per_IL_and_Loc[Income_Level, SubB]) / 3
    ELSE (Accessibility_by_PT_per_IL_and_Loc[Income_Level, Dtwnt] * PCT_Commuters_by_PT[Income_Level, Dtwnt] +
            Accessibility_by_PT_per_IL_and_Loc[Income_Level, SubA] * PCT_Commuters_by_PT[Income_Level, SubA] +
            Accessibility_by_PT_per_IL_and_Loc[Income_Level, SubB] * PCT_Commuters_by_PT[Income_Level, SubB]) / PCT_Commuters_per_IL[Income_Level]
    {dimensionless}

Accessibility_by_Income_Level[Income_Level] = (Accessibility_by_Car_par_Income_Level[Income_Level] *
    ARRAYSUM(Commuters_by_Car[Income_Level,*]) +
    Accessibility_by_PT_par_Income_Level[Income_Level] * ARRAYSUM(Commuters_by_PT[Income_Level,*])
    ) /
    (ARRAYSUM(Commuters_by_Car[Income_Level,*]) + ARRAYSUM(Commuters_by_PT[Income_Level,*]))
{dimensionless}

Beta = 0.1 {dimensionless}

Business_Days_per_Year = 260 {days/year}

Car_Commuters = ARRAYSUM(Commuters_by_Car[*,*])
{people}

Car_Commuters_per_IL[Income_Level] = ARRAYSUM(Commuters_by_Car[Income_Level,*]) {people}

Commuters_per_IL[Income_Level] = ARRAYSUM(Commuters_per_IL_and_Loc[Income_Level,*])
{people}

Commuters_per_IL_and_Loc[Income_Level, Location] = Commuters_by_Car[Income_Level, Location] +
    Commuters_by_PT[Income_Level, Location]
{people}

Commuters_per_Loc[Location] = ARRAYSUM(Commuters_per_IL_and_Loc[*, Location])
{people}
Commuters Switching to Car = -1*Commuters Switching to PT [people]
Commuters Switching to PT = ARRAYSUM(Commuters Switching Mode[*, *]) [people]
Commute Cost by Car[Spatial Separation] = Daily Commute[Spatial Separation] * Business Days per Year *
Commute Cost per Mile by Car [$]
Congestion Index[Spatial Separation] = Commute Time by Car[Spatial Separation] / Free Flow Travel Time by Car[Spatial Separation] [dimensionless]
Cost Based Mode Decision per IL and Spatial Sep[Income Level, Spatial Separation] = Scaling of Mode Decision for Cost per IL[Income Level] * (Perceived Cost Difference[Spatial Separation] / Max Expected Cost[Cost Exponent per IL[Income Level]] [dimensionless]
Cost Difference[Spatial Separation] = ABS(Commute Cost by Car[Spatial Separation] - Commute Cost by PT) [$]
Cost Exponent per IL[Low] = 3 [dimensionless]
Cost Exponent per IL[Mid] = 3 [dimensionless]
Cost Exponent per IL[High] = 3 [dimensionless]
Cost Percent[Spatial Separation] = IF(Commute Cost by Car[Spatial Separation] > Commute Cost by PT)
THEN((Commute Cost by Car[Spatial Separation] - Commute Cost by PT) / Commute Cost by Car[Spatial Separation])
ELSE((Commute Cost by Car[Spatial Separation] - Commute Cost by PT) / Commute Cost by PT) [$/$]
Daily Commute[Dwtn AND SubA] = 17.7 * 2 [mile/day]
Daily Commute[Dwtn AND SubB] = 25.4 * 2 [mile/day]
Daily Commute[SubA AND SubB] = 23.7 * 2 [mile/day]
Daily Commute[Local] = 15 * 2 [mile/day]
Delayed Effect of Spending for PT on Commute Time =
DELAY(Effect of Spending for PT on Commute Time, Delay for PT Implementation) [fraction/year]
Delayed Effect of Spending for Roads on Commute Time =
DELAY(Effect of Spending for Roads on Commute Time, Delay for Road Construction) [fraction/year]
Delay for PT Implementation = 1 [year]
Delay for Road Construction = 2 [years]
Demand Potential by Car[Low,Dwtn] = Commuters per IL and Loc[Low,Dwtn] *
EXP(-1*Beta*Commute Time by Car[Local]) +
Commuters per IL and Loc[Low,SubA] * EXP(-1*Beta*Commute Time by Car[Dwtn AND SubA]) +
Commuters per IL and Loc[Low,SubB] * EXP(-1*Beta*Commute Time by Car[Dwtn AND SubB]) [dimensionless]
Demand_Potential_by_Car[Low, SubA] = Commuters_per_IL_and_Loc[Low, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[Low, SubB] * EXP(-1*Beta*Commute_Time_by_Car[Local]) + 
  Commuters_per_IL_and_Loc[Low, SubB] * EXP(-1*Beta*Commute_Time_by_Car[SubA_AND_SubB]); 
  \{dimensionless\}

Demand_Potential_by_Car[Low, SubB] = Commuters_per_IL_and_Loc[Low, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubB]) + 
  Commuters_per_IL_and_Loc[Low, SubA] * EXP(-1*Beta*Commute_Time_by_Car[SubA_AND_SubB]) + 
  Commuters_per_IL_and_Loc[Low, SubB] * EXP(-1*Beta*Commute_Time_by_Car[Local]); 
  \{dimensionless\}

Demand_Potential_by_Car[Mid, Dwntr] = Commuters_per_IL_and_Loc[Mid, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Local]) + 
  Commuters_per_IL_and_Loc[Mid, SubA] * EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[Mid, SubB] * EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubB]); 
  \{dimensionless\}

Demand_Potential_by_Car[Mid, SubA] = Commuters_per_IL_and_Loc[Mid, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[Mid, SubA] * EXP(-1*Beta*Commute_Time_by_Car[Local]) + 
  Commuters_per_IL_and_Loc[Mid, SubB] * EXP(-1*Beta*Commute_Time_by_Car[SubA_AND_SubB]); 
  \{dimensionless\}

Demand_Potential_by_Car[Mid, SubB] = Commuters_per_IL_and_Loc[Mid, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubB]) + 
  Commuters_per_IL_and_Loc[Mid, SubA] * EXP(-1*Beta*Commute_Time_by_Car[SubA_AND_SubB]) + 
  Commuters_per_IL_and_Loc[Mid, SubB] * EXP(-1*Beta*Commute_Time_by_Car[Local]); 
  \{dimensionless\}

Demand_Potential_by_Car[High, Dwntr] = Commuters_per_IL_and_Loc[High, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Local]) + 
  Commuters_per_IL_and_Loc[High, SubA] * EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[High, SubB] * EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubB]); 
  \{dimensionless\}

Demand_Potential_by_Car[High, SubA] = Commuters_per_IL_and_Loc[High, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[High, SubA] * EXP(-1*Beta*Commute_Time_by_Car[Local]) + 
  Commuters_per_IL_and_Loc[High, SubB] * EXP(-1*Beta*Commute_Time_by_Car[SubA_AND_SubB]); 
  \{dimensionless\}

Demand_Potential_by_Car[High, SubB] = Commuters_per_IL_and_Loc[High, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_Car[Dwntr_AND_SubB]) + 
  Commuters_per_IL_and_Loc[High, SubA] * EXP(-1*Beta*Commute_Time_by_Car[SubA_AND_SubB]) + 
  Commuters_per_IL_and_Loc[High, SubB] * EXP(-1*Beta*Commute_Time_by_Car[Local]); 
  \{dimensionless\}

Demand_Potential_by_PT[Low, Dwntr] = Commuters_per_IL_and_Loc[Low, Dwntr] * 
  EXP(-1*Beta*Commute_Time_by_PT[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[Low, SubA] * EXP(-1*Beta*Commute_Time_by_PT[Dwntr_AND_SubA]) + 
  Commuters_per_IL_and_Loc[Low, SubB] * EXP(-1*Beta*Commute_Time_by_PT[Dwntr_AND_SubB]); 
  \{dimensionless\}
\[
\text{Demand\_Potential\_by\_PT[Low,SubA]} = \text{Commuters\_per\_IL\_and\_Loc[Low,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubA]} + \\
\text{Commuters\_per\_IL\_and\_Loc[Low,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} + \\
\text{Commuters\_per\_IL\_and\_Loc[Low,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[SubA\_AND\_SubB]})} \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[Low,SubB]} = \text{Commuters\_per\_IL\_and\_Loc[Low,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubB]} + \\
\text{Commuters\_per\_IL\_and\_Loc[Low,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[SubA\_AND\_SubB])} + \\
\text{Commuters\_per\_IL\_and\_Loc[Low,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[Mid,Dwn]} = \text{Commuters\_per\_IL\_and\_Loc[Mid,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} + \\
\text{Commuters\_per\_IL\_and\_Loc[Mid,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubA]} + \\
\text{Commuters\_per\_IL\_and\_Loc[Mid,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubB])} \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[Mid,SubA]} = \text{Commuters\_per\_IL\_and\_Loc[Mid,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubA]} + \\
\text{Commuters\_per\_IL\_and\_Loc[Mid,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} + \\
\text{Commuters\_per\_IL\_and\_Loc[Mid,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[SubA\_AND\_SubB]}) \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[Mid,SubB]} = \text{Commuters\_per\_IL\_and\_Loc[Mid,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubB]} + \\
\text{Commuters\_per\_IL\_and\_Loc[Mid,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[SubA\_AND\_SubB])} + \\
\text{Commuters\_per\_IL\_and\_Loc[Mid,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[High,Dwn]} = \text{Commuters\_per\_IL\_and\_Loc[High,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} + \\
\text{Commuters\_per\_IL\_and\_Loc[High,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubA]} + \\
\text{Commuters\_per\_IL\_and\_Loc[High,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubB])} \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[High,SubA]} = \text{Commuters\_per\_IL\_and\_Loc[High,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubA]} + \\
\text{Commuters\_per\_IL\_and\_Loc[High,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} + \\
\text{Commuters\_per\_IL\_and\_Loc[High,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[SubA\_AND\_SubB]}) \\
\{\text{dimensionless}\}
\]

\[
\text{Demand\_Potential\_by\_PT[High,SubB]} = \text{Commuters\_per\_IL\_and\_Loc[High,Dwn]} \times \\
\exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Dwn\_AND\_SubB]} + \\
\text{Commuters\_per\_IL\_and\_Loc[High,SubA]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[SubA\_AND\_SubB])} + \\
\text{Commuters\_per\_IL\_and\_Loc[High,SubB]} \times \exp(-1\times\text{Beta*Commute\_Time\_by\_PT[Local])} \\
\{\text{dimensionless}\}
\]

\[
\text{Desired\_Fraction\_of\_Govt\_Spending\_for\_Roads\_per\_IL[Income\_Level]} = \\
\text{ARRAYSUM(Commuters\_by\_Car[Income\_Level, *])} / \\
(\text{ARRAYSUM(Commuters\_by\_Car[Income\_Level, *])} + \text{ARRAYSUM(Commuters\_by\_PT[Income\_Level, *]))}) \\
\{\text{dimensionless}\}
\]

\[
\text{Discrepancy\_in\_Car\_Travel\_Time[Spatial\_Separation]} = \text{Commute\_Time\_by\_Car[ Spatial\_Separation]} - \\
\text{Free\_Flow\_Travel\_Time\_by\_Car[Spatial\_Separation]} \\
\{\text{min}\}
\]

Effect_of_Change_in_Car_Commuters_on_Commute_Time = Commuters_Switching_to_Car_Car_Commuters * Ratio_of_Increase_in_Car_Commuters_on_Commute_Time {min}  

Effect_of_Decision_on_Commuters_Switching_Modes[income_Level,Location] = Mode_Decision_per_IL_and_Loc[income_Level,Location] {people}  

Fraction_of_Govt_Spending_for_Roads = ARRAYSUM(Weighted_Fraction_of_Govt_Spending_for_Roads_per_IL[*])  

Free_Flow_Travel_Time_by_Car[Dwnn_AND_SubA] = 24 {min}  
Free_Flow_Travel_Time_by_Car[Dwnn_AND_SubB] = 35 {min}  
Free_Flow_Travel_Time_by_Car[SubA_AND_SubB] = 31 {min}  
Free_Flow_Travel_Time_by_Car[Local] = 20 {min}  

Govt_Spending_for_PT = Govt_Spending_on_Transportation - Govt_Spending_for_Roads {$}  

Govt_Spending_for_PT_for_Previous_Year = DELAY(Govt_Spending_for_PT, 1) {$}  

Govt_Spending_for_Roads = Fraction_of_Govt_Spending_for_Roads * Govt_Spending_on_Transportation {$}  

Govt_Spending_for_Roads_for_Previous_Year = DELAY(Govt_Spending_for_Roads, 1) {$}  

Initial_Commute_Time_by_Car[Spatial_Separation] = Initial_Congestion_Index * Free_Flow_Travel_Time_by_Car[Spatial_Separation] {min}  

Initial_Congestion_Index = 1.29 {dimensionless}  

Job_Opportunities_per_IL_and_Loc[Low,Dwnn] = 156725 {jobs}  
Job_Opportunities_per_IL_and_Loc[Low,SubA] = 28696 {jobs}  
Job_Opportunities_per_IL_and_Loc[Low,SubB] = 62944 {jobs}  
Job_Opportunities_per_IL_and_Loc[Mid,Dwnn] = 491851 {jobs}  
Job_Opportunities_per_IL_and_Loc[Mid,SubA] = 216970 {jobs}  
Job_Opportunities_per_IL_and_Loc[Mid,SubB] = 421244 {jobs}  
Job_Opportunities_per_IL_and_Loc[High,Dwnn] = 185069 {jobs}  
Job_Opportunities_per_IL_and_Loc[High,SubA] = 104288 {jobs}  
Job_Opportunities_per_IL_and_Loc[High,SubB] = 322792 {jobs}  

Low_Income_Accessibility_Ratio = Accessibility_per_Income_Level[Low] / Accessibility_per_Income_Level[High] {dimensionless}  

Max_Expected_Cost = 10000 {$}  

Max_Expected_Time = 100 {min}  

Max_PT_Usage_Rate[Low] = 1 {dimensionless}  
Max_PT_Usage_Rate[Mid] = 0.9 {dimensionless}  
Max_PT_Usage_Rate[High] = 0.8 {dimensionless}  

Middle_Income_Accessibility_Ratio = Accessibility_per_Income_Level[Mid] / Accessibility_per_Income_Level[High] {dimensionless}
- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[Low, Dwn]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Dwn\_AND\_SubA]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Dwn\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[Low, SubA]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Dwn\_AND\_SubA]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, SubA\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[Low, SubB]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Dwn\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, SubA\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Low, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[Mid, Dwn]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Dwn\_AND\_SubA]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Dwn\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[Mid, SubA]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Dwn\_AND\_SubA]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, SubA\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[Mid, SubB]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Dwn\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, SubA\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[Mid, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[High, Dwn]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Dwn\_AND\_SubA]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Dwn\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[High, SubA]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Dwn\_AND\_SubA]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, SubA\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Local]}) / 3 \)  
  \{dimensionless\}

- \( \text{Mode\_Decision\_per\_IL\_and\_Lcc[High, SubB]} = \)
  \( (\text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Dwn\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, SubA\_AND\_SubB]} + \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep[High, Local]}) / 3 \)  
  \{dimensionless\}
\( \text{Mode\_Decision\_per\_IL\_and\_Spatial\_Sep}[\text{Income\_Level},\text{Spatial\_Separation}] = \) 
\( \text{Time\_Based\_Mode\_Decision\_per\_IL\_and\_Spatial\_Sep}[\text{Income\_Level},\text{Spatial\_Separation}] + \) 
\( \text{Cost\_Based\_Mode\_Decision\_per\_IL\_and\_Spatial\_Sep}[\text{Income\_Level},\text{Spatial\_Separation}] \) 
\{\text{dimensionless}\}

\( \text{Normal\_Growth\_Rate\_of\_Govt\_Spending} = 0.004 \) \{fraction/year\}

\( \text{Normal\_Rate\_of\_Increase\_in\_Cost\_per\_Mile\_by\_Car} = 0.057 \) 
\{fraction/year\}

\( \text{Normal\_Rate\_of\_Increase\_in\_PT\_Fare} = 0.023 \) \{fraction/year\}

\( \text{Overall\_Accessibility} = (\text{Accessibility\_by\_Car} \times \text{Car\_Commuters} + \text{Accessibility\_by\_PT} \times \text{PT\_Commuters}) / (\text{Car\_Commuters} + \text{PT\_Commuters}) \) 
\{\text{dimensionless}\}

\( \text{Perceived\_Cost\_Difference}[\text{Spatial\_Separation}] = \text{Cost\_Percent}[\text{Spatial\_Separation}] \times \) 
\( \text{Cost\_Difference}[\text{Spatial\_Separation}] \) 
\{$\}$

\( \text{Perceived\_Time\_Difference}[\text{Spatial\_Separation}] = \text{Time\_Percent}[\text{Spatial\_Separation}] \times \) 
\( \text{Time\_Difference}[\text{Spatial\_Separation}] \) 
\{\text{min}\}

\( \text{Percent\_Change\_in\_Spending\_for\_PT} = \text{IF}(\text{Govt\_Spending\_for\_PT} > \) 
\( \text{Govt\_Spending\_for\_PT\_for\_Previous\_Year} \) 
\( \text{THEN}((\text{Govt\_Spending\_for\_PT} - \text{Govt\_Spending\_for\_PT\_for\_Previous\_Year}) / \) 
\( \text{Govt\_Spending\_for\_PT}) \) 
\( \text{ELSE}(\text{Govt\_Spending\_for\_PT} - \text{Govt\_Spending\_for\_PT\_for\_Previous\_Year}) / \) 
\( \text{Govt\_Spending\_for\_PT\_for\_Previous\_Year}) \) 
\{\text{dimensionless}\}

\( \text{Percent\_Change\_in\_Spending\_for\_Roads} = \text{IF}(\text{Govt\_Spending\_for\_Roads} > \) 
\( \text{Govt\_Spending\_for\_Roads\_for\_Previous\_Year} \) 
\( \text{THEN}((\text{Govt\_Spending\_for\_Roads} - \text{Govt\_Spending\_for\_Roads\_for\_Previous\_Year}) / \) 
\( \text{Govt\_Spending\_for\_Roads}) \) 
\( \text{ELSE}(\text{Govt\_Spending\_for\_Roads} - \text{Govt\_Spending\_for\_Roads\_for\_Previous\_Year}) / \) 
\( \text{Govt\_Spending\_for\_Roads\_for\_Previous\_Year}) \) 
\{\text{dimensionless}\}

\( \text{Percent\_Commuters\_Traveling\_by\_PT}[\text{Income\_Level},\text{Location}] = \) 
\( \text{Commuters\_by\_PT}[\text{Income\_Level},\text{Location}] / \) 
\( (\text{Commuters\_by\_PT}[\text{Income\_Level},\text{Location}] + \text{Commuters\_by\_Car}[\text{Income\_Level},\text{Location}]) \) 
\{\text{dimensionless}\}

\( \text{Population} = \text{Car\_Commuters} + \text{PT\_Commuters} \) 
\{\text{people}\}

\( \text{PT\_Commuters} = \text{ARRAYSUM}(\text{Commuters\_by\_PT}[*,*]) \) 
\{\text{people}\}

\( \text{PT\_Commuters\_per\_IL}[\text{Income\_Level}] = \text{ARRAYSUM}(\text{Commuters\_by\_PT}[\text{Income\_Level},*]) \) \{\text{people}\}

\( \text{Public\_Transit\_Accessibility\_Ratio} = \text{Accessibility\_by\_PT} / \text{Accessibility\_by\_Car} \) \{\text{dimensionless}\}

\( \text{Ratio\_of\_Increase\_in\_Car\_Commuters\_on\_Commute\_Time} = 0.119/0.22 \)

\( \text{Remaining\_Car\_Commuters\_Willing\_to\_Switch\_Mode}[\text{Income\_Level},\text{Location}] = \) 
\( (\text{Max\_PT\_Usage\_Rate}[\text{Income\_Level}] - \text{Commuters\_by\_PT}[\text{Income\_Level},\text{Location}] / \) 
\( (\text{Commuters\_by\_PT}[\text{Income\_Level},\text{Location}] + \text{Commuters\_by\_Car}[\text{Income\_Level},\text{Location}]) \) \times \) 
\( \text{Commuters\_by\_Car}[\text{Income\_Level},\text{Location}] \) 
\{\text{people}\}
Scaling of Mode Decision for Cost per IL [Low] = 0.1 \{dimensionless\}
Scaling of Mode Decision for Cost per IL [Mid] = 0.05 \{dimensionless\}
Scaling of Mode Decision for Cost per IL [High] = 0.01 \{dimensionless\}
Scaling of Mode Decision for Time per IL [Low] = 1 \{dimensionless\}
Scaling of Mode Decision for Time per IL [Mid] = 1.5 \{dimensionless\}
Scaling of Mode Decision for Time per IL [High] = 2 \{dimensionless\}
Strength of Opinion In Govt per IL [Low] = 0.1 \{dimensionless\}
Strength of Opinion In Govt per IL [Mid] = 0.3 \{dimensionless\}
Strength of Opinion In Govt per IL [High] = 0.6 \{dimensionless\}

Supply Potential by Car [Low, Dwn] = \text{Job Opportunities per IL and Loc}[Low, Dwn] * \exp(-1*\text{Beta*Commuting Time by Car}[Local]) + \text{Job Opportunities per IL and Loc}[Low, SubA] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubA]) + \text{Job Opportunities per IL and Loc}[Low, SubB] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubB]) \{dimensionless\}

Supply Potential by Car [Low, SubA] = \text{Job Opportunities per IL and Loc}[Low, Dwn] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubA]) + \text{Job Opportunities per IL and Loc}[Low, SubA] * \exp(-1*\text{Beta*Commuting Time by Car}[Local]) + \text{Job Opportunities per IL and Loc}[Low, SubB] * \exp(-1*\text{Beta*Commuting Time by Car}[SubA AND SubB]) \{dimensionless\}

Supply Potential by Car [Low, SubB] = \text{Job Opportunities per IL and Loc}[Low, Dwn] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubB]) + \text{Job Opportunities per IL and Loc}[Low, SubA] * \exp(-1*\text{Beta*Commuting Time by Car}[SubA AND SubB]) + \text{Job Opportunities per IL and Loc}[Low, SubB] * \exp(-1*\text{Beta*Commuting Time by Car}[Local]) \{dimensionless\}

Supply Potential by Car [Mid, Dwn] = \text{Job Opportunities per IL and Loc}[Mid, Dwn] * \exp(-1*\text{Beta*Commuting Time by Car}[Local]) + \text{Job Opportunities per IL and Loc}[Mid, SubA] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubA]) + \text{Job Opportunities per IL and Loc}[Mid, SubB] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubB]) \{dimensionless\}

Supply Potential by Car [Mid, SubA] = \text{Job Opportunities per IL and Loc}[Mid, Dwn] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubA]) + \text{Job Opportunities per IL and Loc}[Mid, SubA] * \exp(-1*\text{Beta*Commuting Time by Car}[Local]) + \text{Job Opportunities per IL and Loc}[Mid, SubB] * \exp(-1*\text{Beta*Commuting Time by Car}[SubA AND SubB]) \{dimensionless\}

Supply Potential by Car [Mid, SubB] = \text{Job Opportunities per IL and Loc}[Mid, Dwn] * \exp(-1*\text{Beta*Commuting Time by Car}[Dwn AND SubB]) + \text{Job Opportunities per IL and Loc}[Mid, SubA] * \exp(-1*\text{Beta*Commuting Time by Car}[SubA AND SubB]) + \text{Job Opportunities per IL and Loc}[Mid, SubB] * \exp(-1*\text{Beta*Commuting Time by Car}[Local]) \{dimensionless\}
\[
\text{Supply\_Potential\_by\_Car[High, Dwtn]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[High, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[High, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[High, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, SubB]}) \text{ (dimensionless)}
\]

\[
\text{Supply\_Potential\_by\_Car[High, SubA]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[High, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[High, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[High, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, SubB]}) \text{ (dimensionless)}
\]

\[
\text{Supply\_Potential\_by\_Car[High, SubB]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[High, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[High, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[High, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_Car[High, SubB]}) \text{ (dimensionless)}
\]

\[
\text{Supply\_Potential\_by\_PT[Low, Dwtn]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, SubB]}) \text{ (dimensionless)}
\]

\[
\text{Supply\_Potential\_by\_PT[Low, SubA]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, SubB]}) \text{ (dimensionless)}
\]

\[
\text{Supply\_Potential\_by\_PT[Low, SubB]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Low, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Low, SubB]}) \text{ (dimensionless)}
\]

\[
\text{Supply\_Potential\_by\_PT[Mid, Dwtn]} = \text{Job\_Opportunities\_per\_IL\_and\_Loc[Mid, Dwtn]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Mid, Dwtn]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Mid, SubA]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Mid, SubA]}) + \\
\text{Job\_Opportunities\_per\_IL\_and\_Loc[Mid, SubB]} \times \exp(-1\times \text{Beta\_Commute\_Time\_by\_PT[Mid, SubB]}) \text{ (dimensionless)}
\]
Supply_Potential_by_PT[Mid, SubA] = Job_Oportunities_per_IL_and_Loc[Mid, Dwn] * 
  \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Dwn\_AND\_SubA]) + 
  Job_Oportunities_per_IL_and_Loc[Mid, SubA] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Local]) + 
  Job_Oportunities_per_IL_and_Loc[Mid, SubB] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[SubA\_AND\_SubB]) 
{\text{dimensionless}}

Supply_Potential_by_PT[Mid, SubB] = Job_Oportunities_per_IL_and_Loc[Mid, Dwn] * 
  \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Dwn\_AND\_SubB]) + 
  Job_Oportunities_per_IL_and_Loc[Mid, SubA] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[SubA\_AND\_SubB]) + 
  Job_Oportunities_per_IL_and_Loc[Mid, SubB] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Local]) 
{\text{dimensionless}}

Supply_Potential_by_PT[High, Dwn] = Job_Oportunities_per_IL_and_Loc[High, Dwn] * 
  \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Dwn\_AND\_SubA]) + 
  Job_Oportunities_per_IL_and_Loc[High, SubA] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Dwn\_AND\_SubB]) + 
  Job_Oportunities_per_IL_and_Loc[High, SubB] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Local]) 
{\text{dimensionless}}

Supply_Potential_by_PT[High, SubA] = Job_Oportunities_per_IL_and_Loc[High, Dwn] * 
  \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Dwn\_AND\_SubA]) + 
  Job_Oportunities_per_IL_and_Loc[High, SubA] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Local]) + 
  Job_Oportunities_per_IL_and_Loc[High, SubB] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[SubA\_AND\_SubB]) 
{\text{dimensionless}}

Supply_Potential_by_PT[High, SubB] = Job_Oportunities_per_IL_and_Loc[High, Dwn] * 
  \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Dwn\_AND\_SubB]) + 
  Job_Oportunities_per_IL_and_Loc[High, SubA] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[SubA\_AND\_SubB]) + 
  Job_Oportunities_per_IL_and_Loc[High, SubB] * \exp(-1*\beta*\text{Commute\_Time\_by\_PT}[Local]) 
{\text{dimensionless}}

Time_Based_Mode_Decision_per_IL_and_Spatial_Sep[Income\_Level, Spatial\_Separation] = 
  \text{Scaling\_of\_Mode\_Decision\_for\_Time\_per\_IL}[Income\_Level] * 
  (\text{Perceived\_Time\_Difference}[Spatial\_Separation] / 
  \text{Max\_Expected\_Time}) * \text{Time\_Exponent\_per\_IL}[Income\_Level] 
{\text{dimensionless}}

Time_Difference[Spatial\_Separation] = \text{ABS}(\text{Commute\_Time\_by\_Car}[Spatial\_Separation] - 
  \text{Commute\_Time\_by\_PT}[Spatial\_Separation]) 
{\text{min}}

Time_Exponent_per_IL[Low] = 3 \{\text{dimensionless}\}

Time_Exponent_per_IL[Mid] = 3 \{\text{dimensionless}\}

Time_Exponent_per_IL[High] = 3 \{\text{dimensionless}\}
Time_Percen[(Spatial_Separation] = IF(Commute_Time_by_Car[(Spatial_Separation] >
Commute_Time_by_PT[(Spatial_Separation])
THEN((Commute_Time_by_Car[(Spatial_Separation] - Commute_Time_by_PT[(Spatial_Separation]) /
Commute_Time_by_Car[(Spatial_Separation)])
ELSE ((Commute_Time_by_Car[(Spatial_Separation] - Commute_Time_by_PT[(Spatial_Separation)]) /
Commute_Time_by_PT[(Spatial_Separation)])
{min/min}

Total_Effect_on_Car Commute_Time = Delayed_Effect_of_Spending_for_Roads_on_Commute_Time +
Effect_of_Change_in_Car_Commuters_on_Commute_Time
{fraction/year}

Total_Effect_on_PT Commute_Time = Delayed_Effect_of_Spending_for_PT_on_Commute_Time -
Hub_Network_Time_Efficiencies
{fraction/year}

Total_Strength_of_Opinion = ARRAYSUM([Strength_of_Opinion_in_Govt per IL[*]) {dimensionless}

Weighted_Fraction_of_Govt_Spending_for_Roads_per_IL[Income_Level] =
Strength_of_Opinion_in_Govt per IL[Income_Level] *
Desired_Fraction_of_Govt_Spending_for_Roads_per_IL[Income_Level]
{dimensionless}

Effect_of_Spending_for_PT_on_Commutes_Time = GRAPH(Percant_Change_in_Spending_for_PT
{dimensionless})
(-1.00, 0.82), (-0.8, 8.21), (-0.6, 0.1), (-0.4, 0.07), (-0.2, 0.03), (-5.5e-017, 0.00), (0.2, -0.03), (0.4, -0.06), (0.6
-0.08), (0.8, -0.12), (1.00, -0.25)

Effect_of_Spending_for_Roads_on_Commute_Time = GRAPH(Percant_Change_in_Spending_for_Roads
{dimensionless})
(-1.00, 0.2), (-0.8, 0.1), (-0.6, 0.05), (-0.4, 0.03), (-0.2, 0.01), (-5.5e-017, 0.00), (0.2, -0.03), (0.4, -0.05), (0.6
-0.1), (0.8, -0.2), (1.00, -0.48)

Hub_Network_Cost_Efficiencies = GRAPH(TIME)
0.00, 0.00, (1.00, 0.136), (2.00, 0.160), (3.00, 0.0892), (4.00, 0.075), (5.00, 0.0593), (6.00, 0.045), (7.00,
0.036), (8.00, 0.0308), (9.00, 0.024), (10.0, 0.018), (11.0, 0.0173), (12.0, 0.0165), (13.0, 0.0135), (14.0,
0.00825), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0,
0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00)

Hub_Network_Time_Efficiencies = GRAPH(TIME)
0.00, 0.001, (1.03, 0.179), (2.07, 0.139), (3.10, 0.117), (4.14, 0.09), (5.17, 0.061), (6.21, 0.042), (7.24,
0.035), (8.28, 0.032), (9.31, 0.024), (10.3, 0.023), (11.4, 0.023), (12.4, 0.018), (13.4, 0.013), (14.5, 0.00),
(15.5, 0.00), (16.6, 0.00), (17.6, 0.00), (18.6, 0.00), (19.7, 0.00), (20.7, 0.00), (21.7, 0.00), (22.8, 0.00), (23.8,
0.00), (24.8, 0.00), (25.9, 0.00), (26.8, 0.00), (27.9, 0.00), (28.0, 0.00), (30.0, 0.00)
Appendix C: Mobility Primary Causes and Consequences

Primary causes and consequences related to mobility were identified based on the Sustainable Mobility Project of the WBCSD and their relationship is summarized in Table 1 (WBCSD, 2001).

Primary Causes

The largest barriers to sustainable mobility are ease of access to the different mobility modes, and the equity of access for people across all demographics. As people gain access to more types of transportation, they are afforded more opportunities to satisfy wants and needs. A large percentage of the population has limited access to personal mobility. The world population's flow into urban settings affects all the other components including ease of access, congestion, emissions, safety, and infrastructure.

Primary Consequences

The effects of the worldwide surge in personal mobility are largely environmental. Conventional and carbon-based emissions have increased to the point of negatively affecting global climate. Urbanization has played a large role in disturbing communities, whether through infrastructure projects that physically divides a town, congestion brought on by over utilization of existing infrastructure, or the isolation caused by increased numbers of cars with solitary drivers.
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<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Nonrenewable Energy Usage</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
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<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td><strong>Total Consequences</strong></td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
<td>3.0</td>
<td>5.0</td>
<td>6.5</td>
<td>6.5</td>
<td>8.0</td>
<td>8.0</td>
<td>3.5</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Total Causes</strong></td>
<td>9.0</td>
<td>9.0</td>
<td>7.0</td>
<td>9.0</td>
<td>7.5</td>
<td>3.5</td>
<td>4.0</td>
<td>2.5</td>
<td>1.5</td>
<td>4.0</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Total Connectivity</strong></td>
<td>14.5</td>
<td>15.0</td>
<td>13.5</td>
<td>12.0</td>
<td>12.5</td>
<td>10.0</td>
<td>10.5</td>
<td>9.5</td>
<td>7.5</td>
<td>11.5</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Table 1. Summary of primary causes (listed vertically), consequences (listed horizontally) and connectivity related to mobility.
Appendix D: Mobility Causal Mapping

Primary causes and consequences from Table 1 are illustrated in the following causal map (Figure 18), showing connectivity among the variables (Morecroft, 2007).

Figure 18. Causal map of mobility.
Appendix E: New Mobility Examples

Traditionally, the public transportation sector has had to compete with the personal automobile sector for finances, access to infrastructure, and even customers. To improve the competitiveness of public transportation, an innovation has surfaced in Bremen, Germany where car-sharing businesses are learning the benefits of cooperating with, rather than competing against, Public Transportation. Car-sharing is the short-term rental of a vehicle, designed to substitute for vehicle ownership. The benefits of encouraging non-ownership are many. It is estimated that on average, cars are idle 22 out of 24 hours per day (UITP, 2002). The total space needed for parking a car at the place of work can be as high as 90 times that needed for a pedestrian using public transport. In peak hours a bus carries as much as ten times the number of passengers that can be carried by private cars using the same space (Rat, Urbanicity). For the community, the main benefits of car-sharing are the reduction in the number of cars, the use of newer, smaller cars, and the reduction in total distance driven. The VBZ, a public transport operator in Bremen, is developing into a customer-oriented personal mobility service supplier. It partners with Europcar and Mobility Car Sharing Schweiz to offer services such as:

- A network of public transport stations with an integrated fare structure
- A network of car-sharing stations
- Additional specialty services like holiday rentals, cargo vehicles, etc.

A more recent innovation, referred to as New Mobility hub networks, began in Bremen, Germany building off of the car sharing businesses discussed above, and is evolving and spreading to a number of other European cities, as well as to Toronto, Canada. New Mobility hubs “connect a variety of sustainable modes of transportation and services through a network of
physical locations throughout a city or region, physically and electronically linking the elements necessary for a seamless, integrated, sustainable door-to-door urban trip” (MTE, 2004). Hubs are practical for cities in the developed or developing world because they are scalable, flexible, and can be customized to fit local needs, resources, and aspirations. Hubs can link and support a variety of diverse elements (Zielinski, 2006):

- Multiple transportation operators, modes, and services
- Taxis and car-sharing of a variety of vehicle types and sizes
- “Slugging” (Slug-Lines.com, 2006)
- Free or fee-for-use bicycle sharing (Bikeshare/CBN, 2006)
- Walkable, bikable, and transit-oriented spatial design and development (Kelbaugh, 1997)
- Cafes and meeting places
- Wi-fi amenities
- Electronic fare-payment options and pricing mechanisms for all transportation modes and services
- Satellite-enhanced, real-time, urban traveler information for all modes of transportation provided at on-street kiosks and by pda

Another New Mobility example is the Hong Kong Octopus. The Hong Kong Octopus card is a universal payment system that rests on a smartcard. Reload-able debit cards have been in use for many years, but the uniqueness of the Octopus is its universal acceptance for many different types of transportation. In Hong Kong, the entire public transport industry operates on the assumption that all riders carry the Octopus card. At many terminals, cash payments are highly discouraged, or simply not allowed. The card works at all commuter rail lines, buses, trams,
ferries, a few department and convenience stores and even McDonalds (Bailey, 2003). Kiosks in terminals also allow rapid reloading of cards. Simply wave your card over a card reader as you approach a turnstile and it will flash you the remaining balance as you are purchasing a fare.
References


Gladwin, Tom and Zielinski, Sue. Interview by authors. Ann Arbor, Mi, April 13, 2008.


Macomb County Road Commission, 2008. Available online at: 


MTE (Moving the Economy). 2004. “Bremen and Toronto New Mobility Hub Case Studies and Day in the Life Scenario”. Available online at: 
http://www.movingtheeconomy.ca/content/csPDF/BremenVideoSummaryAug2.pdf, 
http://www.movingtheeconomy.ca/content/mte_hubAbout.html, and 
http://www.movingtheeconomy.ca/content/ditl.html.


Octopus. 2006. Available online at:


Rat, Hans. “Public Transport: A Mobility Market in Transformation”. Available online at: 


Skerlos, Steve. Interview by authors. Ann Arbor, MI, March 7, 2008.


SMART, 2008. Available online at: 
http://www.smartbus.org/Smart/Ride+SMART/Fares+and+Tickets

http://mobility.tamu.edu/ums/.

(TTI) Texas Transportation Institute, 2008. Available online at: 
http://mobility.tamu.edu/ums/congestion_data/tables/national/table_5.pdf


Wingfield, Eric. Interview by authors. Ann Arbor, Mi, March 6, 2008.


THE DIFFUSION OF HYBRID ELECTRIC VEHICLES

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INTRODUCTION

Mass produced hybrid electric vehicles (HEVs) first became available in the U.S. Market in December of 1999. Since then a host of celebrities have traded in their luxury sedans for hybrids [2], and the President of the United States has given hybrids prominent mention in his State of the Union address and numerous other speeches. Despite this attention, just over one million HEVs have been sold in North America since their introduction. In 2007, the best year yet for HEV sales, HEVs accounted for around 2% of total U.S. light vehicle sales [4, 6]. Are hybrids destined to be a niche vehicle, adopted only by a small wealthy and environmentally conscious population or is hybrid technology destined to become a standard addition to any internal combustion engine?

In this note, I compare the diffusion of HEVs to previous automotive innovations. I then examine the forecasts of two simple diffusion models applied to current HEV adoption data. These models illustrate scenarios in which the trend of hybrid adoption in the future follows the same pattern of growth that it has in the past.

COMPARATIVE EXAMPLES

One source of insight into the potential future of HEVs is the historical evolution of other vehicle innovations. In this section, I briefly consider two that followed drastically different pathways: minivans and airbags.

Chrysler introduced the Dodge Caravan at the end of 1983 and captured 1.58% of the new car market in 1984. Total minivan sales in
the U.S. exceeded 2.25 million just five years after their introduction. Chrysler captured over half of these sales, with 1.3 million sales in the first five years [12]. By 1997, 14 different types of minivans were being produced by six different manufacturers, but Chrysler continued to dominate the market, capturing 44% of annual sales that year. While the minivan all but eliminated the station wagon as a vehicle segment, it remained a niche vehicle (later to be crowded by the sport utility vehicle and then the crossover – itself a close relative of the original station wagon).

Compared to the minivan, HEVs have diffused slowly. In 2000, their debut year on the market, fewer than ten thousand were sold. However, many other aspects of the HEV diffusion path are similar to those of the minivan. The number of manufacturers producing hybrids and the number of available models has increased significantly. In 2000, Honda and Toyota each produced a single HEV model. Today there are at least eighteen HEV models available from ten different brands (five manufacturers). As in the case of the minivan, HEV sales are dominated by a single manufacturer. In 2007, 81% of HEV sales were Toyota or Lexus hybrids. More than 50% of 2007 HEV sales were of the Prius alone [4]. If these similarities indicate that HEVs are analogous to minivans, there is little hope for significant market penetration (and thus for corresponding reduction in oil consumption and greenhouse gas emissions [15]).

Hybrid technology, unlike the minivan innovation, can also be thought of as an addition to current production vehicles. All but one of the currently available HEV models are also available in a non-hybrid version (the Toyota Prius being the sole exception). In this sense, HEV technology may be more similar to other technology advances such as safety features like automatic seatbelts, airbags, antilock brakes and electronic stability control.

Airbags provide an interesting case for comparison. The early development of airbags was heavily influenced by government safety regulations, just as increased fuel economy and emissions standards today are encouraging the development of hybrid vehicles. Airbags as an option also came at a significant price premium; a driver-side airbag on a 1986 Ford Tempo raised the price of the car $815 [13]. Similarly, a 2009 Toyota Camry Hybrid costs around $4000 more than a similar standard Camry [1].

Airbags followed a very different adoption path from minivans. Airbags were first offered on vehicles available for public sale in 1973. By 1988, fifteen years later, only two percent of new cars were airbag equipped [9]. A rapid increase in consumer adoption followed this relatively slow
initial diffusion, and in 1991 Congress passed legislation requiring all new vehicles to be equipped with dual front airbags by 1998.

**Diffusion models**

A second method for forecasting the HEV diffusion path is to look at the current adoption trend and extrapolate into the future. Extrapolation methods are, “reliable, objective, inexpensive, quick, and easily automated.” [3] Here, I examine the forecasts of two common diffusion models: the Bass model and the Gompertz model. The models are fit to U.S. monthly vehicle registration data from February, 2001 to October, 2007. Registration data are used as a proxy for sales.

The adoption curves from the two models fit to the data along with the data are shown in Figure 1. The predictions of the two models are quite different. The predicted total market penetration for the Gompertz model is around sixteen times greater than that of the Bass...
model. While the Bass fit predicts that monthly hybrid adoptions begin to slow after the summer of 2008, the Gompertz fit predicts that sales continue to increase until 2015.

The website hybridcars.com collected several forecasts of annual hybrid sales from firms such as J.D. Power and ABI Research [5]. Figure 2 displays those forecasts alongside the Bass and Gompertz forecasts calculated here. The forecasts appear to fall along two trajectories, those that expect hybrid penetration to grow at an increasing rate, and those that expect hybrid penetration to begin to slow in the near future. These two paths mirror the forecasts of the two diffusion models, except that the Gompertz model predicts a less steep continuation in penetration and the Bass model predicts an even more rapid drop off in adoption.

In a review of the application of diffusion models to marketing, Mahajan et al. [8] state that, “studies suggest that stable robust parameter estimates for the Bass model are obtained only if the data under consideration include the peak of the noncumulative adoption curve,” and that, “parameter estimation for diffusion models is primarily of historical interest; by the time sufficient observations have developed for reliable estimation, it is too late to use the estimates for forecasting purposes.” Nevertheless, these authors and others still advocate the use of the Bass model and its extensions as a predictive tool, but in
conjunction with exogenous parameter estimates, particularly for the market ceiling $m$ [11, 16].

Rao [7] and Meade and Islam [10] compare the predictive accuracy of several diffusion models. Both studies conclude that simpler models tend to outperform those that are more complex. In Rao’s comparison, the Gompertz model was the most consistently accurate prediction curve. The Gompertz model was also among the top performers in Meade and Islam’s study. Given the results of these studies, and some issues with fitting the Bass model to partial adoption data discussed in the following section, it seems safest to give most weight to the predictions of the Gompertz model in the case of HEVs.

**TECHNICAL NOTES ON MODEL FITTING**

The Bass model is fit to the data using the nonlinear least squares method advocated by Srinivasan and Mason [14]. In this method, the probability density function $f(t)$ for adoption at time $t$ is integrated to give the cumulative distribution function $F(t)$. Then sales in period $i$ are modeled as

$$X(i) = m[F(t_i) - F(t_{i-1})] + u_i,$$

where $u_i$ is an additive error term with mean zero. The parameters of the model are estimated by fitting $X(i)$ to the data using nonlinear least squares.

Nonlinear least squares estimates of Bass model parameters based on partial adoption data are known to be biased [16]. This means that even if the diffusion process follows the pattern specified by the Bass model, estimates of the parameters in the model based on partial adoption data will be systematically different from the true parameter values. Specifically, estimates of $m$ and $p$ tend to be biased downwards while estimates of $q$ tend to be biased upwards. This bias decreases when the data contain more frequent observations, and when observations further along in the diffusion process are added. I have the advantage in this study of using monthly HEV adoption data, while all other studies that I am aware of have used annual adoption data. Van den Bulte and Lillien [16] suggest that the market ceiling $m$ is commonly underestimated by as much as twenty percent. Despite this bias, a comparison of the nonlinear least squares method of parameter estimation with other available methods concluded that the nonlinear least squares method is superior [8].

The parameters of the Gompertz model are estimated by directly fitting the Gompertz equation to the empirically observed number of cumulative adoptions, again using nonlinear least squares.
For both models, all estimated parameters are significantly different from zero.

CONCLUSION

Based on the historical comparisons with minivans and airbags, there are two potential views of the future of hybrid electric vehicles. On the one hand, they may be a niche vehicle that satisfies the needs of a specific portion of the population but that has little impact on the majority of drivers, as was the case with the minivan. On the other hand, they may function as an add-on to existing vehicles with the potential to eventually become standard on all vehicles, as in the case of airbags.

Comparative studies of extrapolation models tend to favor the Gompertz model to the Bass model. Although the Gompertz model forecasts greater market penetration than the Bass model, even this model predicts only limited total market penetration. If HEVs are to follow the path of airbags and become standard vehicle equipment, this analysis seems to indicate that, like airbags, hybrid technology will need to benefit from substantial assistance from government regulation or a massive shift in public opinion regarding the value of environmentally friendly products.

REFERENCES


The Robustness of Scale-Free Networks

Purpose of the Model

The goal of this model is to evaluate how a nearly scale-free transportation network\(^1\) can withstand and rebound from various disruptions and node failures.

According to Barabasi and Bonabeau, a scale-free network is a network where some highly connected nodes have an almost unlimited number of connections and no node is typical of the others (Barabasi and Bonabeau, Scale-Free Networks). Unlike random networks where each node is connected to another by random links, in a scale-free network the nodes are connected via preferential attachment. This method of attachment leads to some nodes having a greater number of links to many other nodes in the network. These greater numbers of links between nodes insulates the network from small random node failures since there are many other routes that can be taken in the network. A network is said to be robust if there large number of options in a network to get from node to node. The more robust a network is the more resilient it should be to node failure (Crucitti, Latora and Marchiori).

The World Wide Web, spread of a new viral marketing campaign, and the sexual patterns of Swedish adults are all examples of scale-free networks (Barabasi, Publications:Talks). A new mobility hub network is an example of a scale-free transportation network. A new mobility hub network is a network of hubs which provide just in-time transportation and access of a variety of transportation modes (ex. subway, taxis, cars, and buses). It is hypothesized that a new mobility hub network would reduce congestion and improve system efficiency through encouraging ride sharing or use of public transit, reduce the need for motorized trips through encouraging urban design centered around key hubs which reduces travel time, and increasing accessibility to underserved populations through making transportation more affordable.

To better understand the robustness and resilience of the New Mobility hub network, we examined the impact of disturbance or attack on the system. Since we are examining a transportation system there are many different attacks or disturbances that could take place. They could range from a terrorist attack to an earthquake to a fire at a subway station. Most experts in the field of scale-free networks believe that scale-free networks are highly tolerant to random failures. So, for our network if a bus station is closed for some reason, the entire transportation system will not close down. But at the same time, these scale-free networks are highly susceptible to targeted attacks at highly connected nodes or hubs (Newth and Ash). So, if a terrorist were to blow up Grand Central Station, it would affect

\(^1\) Transportation networks can never be truly scale-free because of limitations on where it is possible to build the required infrastructure. For this thought exercise, we are assuming that it would be possible to make a close approximation to a scale-free transportation network though implementing the ideals of a new mobility hub network.
not only the trains in New York, but also the buses and the taxis possibly crippling the transportation system.

**Model Definition and Key Variables**

Our model is made up of three major sections:

- **Nodes and Connections** – This is the number of nodes that exist in our network and their associated connections or links.
- **Critical Hubs** – This is the number of highly connect nodes (hubs) that exist in our network.
- **Efficiency** – This represents how quickly or efficiently a user of the network can move from their initial location to their desired location.

Additionally, we have designed the model to take into account the concept of the hub network efficiencies. It is theorized that by taking an already existing transportation network and converting it to a new mobility hub network that the number of connections (links) between nodes will increase at greater rate than a “normal” network because of the inherent interconnectedness of a new mobility hub network.

The following table outlines the all of the variables in our model.

<table>
<thead>
<tr>
<th>Key Variable (include units)</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes (nodes)</td>
<td>The number of nodes that exist in a network.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td><strong>Increase in Nodes (nodes)</strong></td>
<td>The amount increase in the number of nodes in the network.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
<td>----------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td><strong>Node Growth (%)</strong></td>
<td>The percent that the number of nodes grow per year.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Decrease in Nodes (nodes)</strong></td>
<td>The amount decrease in the number of nodes in the network due to attacks.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td><strong>Connections (connections)</strong></td>
<td>The number of links that currently exist in the network.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td><strong>Increase in Connections (connections)</strong></td>
<td>The amount increase in the number of connections in the network.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td><strong>Connect Growth Rate (%)</strong></td>
<td>The rate at which the number of connections increases per year.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Hub Network Effect on Connections (%)</strong></td>
<td>The positive effect that hub networks can have on the growth of connections in the network. (This is a graphical function in our model.)</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Decrease in Connections (connections)</strong></td>
<td>The amount decrease in the number of connections in the network.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td><strong>Government Policy (%)</strong></td>
<td>The percentage chance that government policies like law enforcement or even building codes have on decreasing the likely hood of an attack or disruption. (This is a graphical function in our model.)</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Chance of Attack</strong></td>
<td>The percentage chance that an attack or disruption will occur at any given time.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Attack?</strong></td>
<td>If an attack or disruption occurs in the given year (t). (This is driven by a random number generator driven by the probability of attack.)</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>The maximum amount of damage that can</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Damage (%)</td>
<td>occur during an attack or disruption.</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Damage per Attack (%)</td>
<td>The amount of damage that takes place in a given year if an attack or disruption occurs.</td>
<td>Endogenous Converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial nodes (nodes)</td>
<td>The number of nodes that initially exist in the network.</td>
<td>Exogenous Converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial connections (connections)</td>
<td>The number of connections (links) that initially exist in the network.</td>
<td>Exogenous Converter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Critical Hubs

<table>
<thead>
<tr>
<th>Key Variable</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Hubs (hubs)</td>
<td>The number of critical hubs that exist in the network.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td>Increase in hubs (hubs)</td>
<td>The increase in the number of hubs in a given year.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Decrease in hubs (hubs)</td>
<td>The decrease in the number of hubs in a given year.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Initial hubs (hubs)</td>
<td>The initial number of hubs in the network.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Maximum Critical Hubs</td>
<td>The maximum number of hubs that could possibly form in the network.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Cluster Coefficient</td>
<td>A ratio of nodes to connections that is being used to determine when a hub is formed.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Effect of cluster coefficient on critical hubs</td>
<td>The effect that the cluster coefficient has on hub formation. (This is a graphical function in our model.)</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Hub Damage</td>
<td>The number of hubs that will be affected by an attack or disruption in the network.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
</tbody>
</table>
### Hub Attack

Determines if a hub is one of the nodes that is attacked or disrupted in a given year. (This is driven by a random number generator that is triggered only if there is an attack in a given year.)

### Efficiency

<table>
<thead>
<tr>
<th>Key Variable</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>The efficiency at which the network is operating. This is expressed as a number from 0 to 1.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td>Change in Efficiency</td>
<td>The amount that the efficiency changes based on node, connection and hub growth and the effects of attacks or disruptions.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Initial Efficiency</td>
<td>The initial level of efficiency in the network.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Fixer</td>
<td>This fixes a ghost in the model that occasionally caused errors when the number of critical hubs was at the maximum allowable amount. Otherwise this has no effect on the model.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Effect of critical hubs on efficiency (%)</td>
<td>This is the percentage change that change in efficiency that critical hubs can have on the network.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Fixer 2</td>
<td>This fixes a ghost in the model that occasionally caused errors when the number of connections is 0 after a massive attack or disruption. Otherwise this has no effect on the model.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Effect of connections on efficiency (%)</td>
<td>This is the percentage change that change in efficiency that connections can have on the network.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Effect of nodes on efficiency (%)</td>
<td>This is the percentage change that change in efficiency that the number of nodes can have on the network.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
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<td></td>
</tr>
<tr>
<td>Net effect</td>
<td>This is the summed effect of the effect of nodes, effect of connections, and effect of critical hubs on efficiency.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
</tbody>
</table>

**Reference Behavior Pattern**

The model we have constructed is a hypothesized model based on the implementation of a new mobility hub network that experience random attacks or disruptions of random magnitude. The model assumes that a hub network is implemented today and the results are modeled over a fifty year time period. This model is compared to a base case where no hub network is implemented.

**Basic Mechanisms and Organizing Principles**

Assuming there are no attacks or disruptions in the system, if a hub network is not implemented, we anticipate that the number of interconnections between the nodes will grow at a slow pace. Because of the concept of preferential attachment, the connections made will most likely be to already highly connected nodes. This will lead to more critical hubs forming. Efficiency will continue to grow at a slow pace. If there is an attack or disruption, then assuming that the system isn’t totally destroyed, it should recover at a slow pace.

We anticipate that the implementation of the new mobility hub network greatly increase the number of interconnections in the network. This will improve the speed at which the system efficiency grows. It will also slow the growth of critical hubs in the network. If there is a non-catastrophic attack or disruption, the hub network will lead to a faster system recovery.

Our dynamic hypothesis is that although critical hubs help the system efficiency grow at a faster pace, their disruption due to an attack has a great effect on the overall system efficiency. New mobility hub networks slow the growth of these critical hubs from forming. Hence, a new mobility hub network transportation system should be more resilient to attack than a standard system.

**Hub Network Benefits**

Because the base theory of a new mobility hub network is to integrate all the existing modes of transportation in a connected network, it is believed that instituting a new mobility hub network will increase the number of connections between nodes in the network. While the exact sources of this benefit and specific percentages cannot be known precisely without extensive study of a specific transportation system, it is assumed that the new system will increase the number of connections between all of the nodes. However, it is assumed that a system cannot reach total connectedness
(when every node is attached to every other node); therefore the benefit of the hub network will wane over time. Figure 3 is the graph of what we assume the hub network benefit will be.

**Figure 3: Assumed Hub Network Benefit to the Growth of Connections**

![Graph showing assumed hub network benefit over time](image)

**Network Robustness**

There have been many studies conducted on the robustness of networks. The works of Barabasi, Crucitti, Newman and others all point out that a scale-free network is extremely robust to random attack on outlaying nodes. But these highly efficient and well connected networks are vulnerable to attacks on a few key nodes, called critical hubs. It has been theorized that the world-wide internet, a truly scale-free network, could be crippled by targeted attacks on as few as 15 routers (Barabasi, The Architecture of Complexity).

Further, experts believe that the very fact that these networks are so interconnected can lead to some unforeseen negative side effects. There is the threat of scale-free epidemics. This is when one node gets infected, in the case of transportation this could be congestion, it is passed along throughout the network until all nodes are affected. This has been seen in many scale-free networks, but perhaps one of the most recent events was the explosion and spread of the love-bug computer virus (Barabasi and Bonabeau, Scale-Free Networks). These epidemics can also be seen as local failures causing global problems. An example of this cascading effect is the largest blackout in the history of the United States. On August 14 2003 a disturbance in the power grid in Ohio led to most of the northeastern United States being without power (Newth and Ash).
Parameter Values

In setting our base variable values, we used Bangalore, India as a reference point. For the variables that do not have hard data, especially the effect that hub networks can have on the cost and time required for transportation, we have used graphs that clearly show our assumptions.

<table>
<thead>
<tr>
<th>Nodes and Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable</strong></td>
</tr>
<tr>
<td>Nodes (nodes)</td>
</tr>
<tr>
<td>Increase in Nodes (nodes)</td>
</tr>
<tr>
<td>Node Growth (%)</td>
</tr>
<tr>
<td>Decrease in Nodes (nodes)</td>
</tr>
<tr>
<td>Connections (connections)</td>
</tr>
<tr>
<td>Increase in Connections (connections)</td>
</tr>
<tr>
<td>Connect Growth Rate (%)</td>
</tr>
<tr>
<td>Hub Network Effect on Connections (%)</td>
</tr>
<tr>
<td>Decrease in Connections (connections)</td>
</tr>
<tr>
<td>Government Policy (%)</td>
</tr>
<tr>
<td>Chance of Attack</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Attack?</td>
</tr>
<tr>
<td>Maximum Damage (%)</td>
</tr>
<tr>
<td>Damage per Attack (%)</td>
</tr>
<tr>
<td>Initial nodes (nodes)</td>
</tr>
<tr>
<td>Initial connections (connections)</td>
</tr>
</tbody>
</table>

### Critical Hubs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Assumption/Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Hubs (hubs)</td>
<td>This is assumed to grow as a function of the cluster coefficient.</td>
</tr>
<tr>
<td>Increase in hubs (hubs)</td>
<td>A function of cluster coefficient</td>
</tr>
<tr>
<td>Decrease in hubs (hubs)</td>
<td>A function of damage done to the hubs by an attack or disruption</td>
</tr>
<tr>
<td>Initial hubs (hubs)</td>
<td>1. This is an assumed value. It was chosen to represent a small scale transportation network.</td>
</tr>
<tr>
<td>Maximum Critical Hubs</td>
<td>10. This is an assumed value. It was chosen to represent a small scale transportation network.</td>
</tr>
<tr>
<td>Cluster Coefficient</td>
<td>Assumed to be number of connections divided by the number of nodes times the number of nodes minus 1.</td>
</tr>
<tr>
<td>Effect of cluster coefficient on</td>
<td>0 or 1. This is based on a random number generator that makes the probability of</td>
</tr>
<tr>
<td>Critical Hubs</td>
<td>Getting a 1 (when new critical hub is formed) a function of the cluster coefficient.</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Hub Damage</td>
<td>A random integer between 0 and the current number of hubs.</td>
</tr>
<tr>
<td>Hub Attack</td>
<td>0 or 1. This is based on a random number generator that makes the probability of getting a 1 (when a critical hub is attacked) a function of the Chance of Hub Attack if and only if there is an attack or disruption in the network.</td>
</tr>
</tbody>
</table>

**Efficiency**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Assumption/Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Efficiency</td>
<td>Assumed to chance with as the net effect chances and cannot go over 1.</td>
</tr>
<tr>
<td>Initial Efficiency</td>
<td>40%. This is an assumption based on average efficiencies in scale free networks.</td>
</tr>
<tr>
<td>Effect of critical hubs on efficiency (%)</td>
<td>This is a graphical function. This assumed shape is based on a best guess on how highly connected nodes can improve network efficiency.</td>
</tr>
<tr>
<td>Effect of connections on efficiency (%)</td>
<td>This is a graphical function. This assumed shape is based on a best guess on how increasing or decreasing the number of connections within a network can affect network efficiency.</td>
</tr>
<tr>
<td>Effect of nodes on efficiency (%)</td>
<td>This is a graphical function. This assumed shape is based on a best guess on how increasing or decreasing the number of nodes can affect network efficiency.</td>
</tr>
<tr>
<td>Net effect</td>
<td>This is the sum of the effects of critical hubs, connections, and nodes have on efficiency.</td>
</tr>
</tbody>
</table>

**Test Dynamic Hypothesis**

**Base Case**

For this model, we assume the base case is when there are no attacks or disruptions and there is no hub network benefit. Figure 4 is the output from the model under these situations. Here you can see that
the number of critical hubs form quite quickly\textsuperscript{2}. Also note that the efficiency, number of nodes, and number of connections all grow at a steady pace.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{base_case_output_graph.png}
\caption{Base Case Output Graph}
\end{figure}

\textit{Hub Network Effects}

Next, we examined the effects that a new mobility hub network could have on our transportation system. Figure 5 is the output graph from the model to demonstrate the hub network effect. Note that as in the base case, we do not have any attacks or disruptions occurring in the system. Here you can see that the hub network did indeed improve the number of connections between the nodes (around 500 vs. 150 for the base case). It also sped the growth of critical hubs leading to a high level of efficiency.

\textsuperscript{2} The fluctuation in the number of critical hubs is due to how the number of hubs is regulated by the maximum number of hubs. At no time does a critical hub actually leave the network in this case.
Attacks

The next case we looked at was when a system has an attack or disruption. We first ran the model with the base case and allowed random attacks take place. Figure 6 shows the effect on the transportation system. Figure 7 shows when and how severe the attacks or disruptions were.
Here we can see that two relatively low intensity disruptions occur around years 36 and 42. In Figure 6, you can see how this impacted the efficiency and number of nodes and connections. It is more interesting to see what happens when the attack or disruption takes place at a critical hub. Figure 8 shows how disastrous an attack on the critical hubs can be. Note that after this attack, the system completely crashes (0% efficiency), even though there are still some nodes, hubs, and connections still available.
Sensitivities and Policy Levers

Next we were interested in checking how sensitive our model was to changes in a select number of variables. We have tried to focus on the variables that will help prove our dynamic hypothesis that hub networks, through increasing the number of connections between nodes, improve the robustness of the transportation network. Therefore, we ran the model several times when attacks occur with varying degrees of hub network benefits. As expected, when the hub network benefit adds a great number of connections between nodes, there are fewer critical hubs. This further insulates the network from disruption from random attacks. But, if a targeted attack\(^3\) occurs, the system can be found to crash much more frequently due to the loss of these critical hubs.

We have also built in extremely generalized policy levers that a government could use to try to deal with these random attacks. These measures could be anything from increase police presence to designing the infrastructure in the network to be more attack resistant. Because this model is fairly simple, it is possible for governments to completely eradicate the threat of these random disruptions but in reality there would be no way for there ever to be a 100% guarantee of safety.

Ways to Improve the Model

Finally, we thought about how we could improve this model if we had more time and resources. First off, I think that this model could be significantly improved if you could properly represent the network spatially. We could not use Stella to do this. If we were able to have a spatial sense of where these random disturbances take place, we could more accurately model their affects on the system efficiency. Second, more work should be done to model the threat of attack. For this model, all we could do was make very general assumptions. Finally, more time could be spent to better define the government policies that will affect the chance of attack. There is a chance that government efforts in this area may actually lead to an increase threat of attack.

\(^3\) For this case a targeted attack is when Chance of Attack on Hub is 100%.
Bibliography


Appendix A: Equation List

- \( \text{Attack} = \text{IF}((\text{Chance_of_Attack} - \text{Government_Policy}) > 0) \) THEN
  - \( \text{MONTECARLO}((\text{Chance_of_Attack} - \text{Government_Policy}) \) ELSE 0
- \( \text{Chance_of_Attack_on_Hub} = 20 \)
- \( \text{Cluster_Coefficient} = \text{Connections}/(\text{Nodes}^2) \)
- \( \text{Connect_Growth_Rate} = .1 \)
- \( \text{Damage_per_attack} = \text{RANDOM}(0, \text{Maximum_Damage}) \)
- \( \text{Effect_of_Clustering_on_Critical_Hubs} = \text{MONTECARLO}(100 - \text{Cluster_Coefficient} 	imes 100) \)
- \( \text{Fixer} = \text{IF}((\text{Critical_Hubs} = 10) \) OR (Critical_Hubs = 11) \) THEN 0 ELSE 1
- \( \text{Fixer}_2 = \text{IF}((\text{Connections} = 0) \) THEN 1 ELSE 0 \)
- \( \text{Hub_Attack} = \text{IF}(\text{Attack} = 1) \) THEN \( \text{MONTECARLO}((\text{Chance_of_Attack} - \text{on_Hub}) \) ELSE 0
- \( \text{Hub_Damage} = \text{ROUND}(\text{RANDOM}(1, \text{Critical_Hubs})) \)
- \( \text{Initial_Connections} = 7 \)
- \( \text{Initial_Efficiency} = .4 \)
- \( \text{Initial_Hubs} = 1 \)
- \( \text{Initial_Nodes} = 5 \)
- \( \text{Maximum_Critical_Hubs} = 10 \)
- \( \text{Maximum_Damage} = .5 \)
- \( \text{Net_Effect} = \text{Effect_of_Connections_on_Efficiency} + \text{Effect_of_Critical_Hubs_on_Efficiency} + \text{Effect_of_Nodes_On_Efficiency} \)
- \( \text{Node_Growth} = .05 \)
- \( \text{Chance_of_Attack} = \text{GRAPH(TIME)} \)
- \( (0.00, 10.0), (4.17, 10.0), (3.33, 10.0), (12.5, 10.0), (16.7, 10.0), (20.8, 10.0), (25.0, 10.0), (29.2, 10.0), (33.3, 10.0), (37.6, 10.0), (41.7, 10.0), (45.8, 10.0), (50.0, 10.0) \)
- \( \text{Effect_of_Connections_on_Efficiency} = \text{GRAPH}((\text{Connections} - \text{HISTORY(Connections, TIME-1)})/(\text{Connections} + \text{Fixer}_2)) \)
- \( (-1.00, -0.738), (-0.8, -0.4), (-0.6, -0.2), (-0.4, -0.15), (-0.2, -0.075), (-5.55e-017, 0.00), (0.2, 0.05), (0.4, 0.1), (0.6, 0.113), (0.8, 0.25), (1.00, 0.5) \)
- \( \text{Effect_of_Critical_Hubs_on_Efficiency} = \text{GRAPH}((\text{Critical_Hubs} - \text{HISTORY(Critical_Hubs, TIME-1)})/(\text{Critical_Hubs} + \text{Fixer})) \)
- \( (-1.00, -0.97), (-0.8, -0.6), (-0.6, -0.5), (-0.4, -0.2), (-0.2, -0.1), (-5.55e-017, 0.00), (0.2, 0.01), (0.4, 0.02), (0.6, 0.04), (0.8, 0.08), (1.00, 0.15) \)
- \( \text{Effect_of_Nodes_On_Efficiency} = \text{GRAPH}((\text{Nodes} - \text{HISTORY(Nodes, TIME-1)})/(\text{Nodes})) \)
- \( (-1.00, -0.425), (-0.8, -0.3), (-0.6, -0.25), (-0.4, -0.2), (-0.2, -0.1), (-5.55e-017, 0.00), (0.2, 0.006), (0.4, 0.01), (0.6, 0.015), (0.8, 0.04), (1.00, 0.15) \)
- \( \text{Government_Policy} = \text{GRAPH}(\text{TIME}) \)
- \( (0.00, 10.0), (4.17, 10.0), (3.33, 10.0), (12.5, 10.0), (16.7, 10.0), (20.8, 10.0), (25.0, 9.00), (29.2, 8.00), (33.3, 7.00), (37.6, 6.00), (41.7, 5.00), (45.8, 4.00), (50.0, 1.00) \)
- \( \text{Hub_Network Effect on Connections} = \text{GRAPH}(\text{TIME}) \)
- \( (0.00, 0.00), (5.00, 0.2), (10.0, 0.33), (15.0, 0.405), (20.0, 0.45), (25.0, 0.505), (30.0, 0.515), (35.0, 0.45), (40.0, 0.3), (45.0, 0.235), (50.0, 0.23) \)
\[
\text{Connections}(t) = \text{Connections}(t - dt) + (\text{Increase_in_Connections} - \text{Decrease_in_Connections}) \cdot dt
\]
\[
\text{INIT} \quad \text{Connections} = \text{Initial_Connections}
\]
\[
\text{INFLOWS:}
\]
\[
\text{Increase_in_connections} =
\]
\[
((\text{Hub_Network_Effect_on_Connections} + \text{Connect_Growth_Rate}) \cdot \text{Nodes}) + (\text{Nodes_history}(\text{nodes, time-1}))
\]
\[
\text{OUTFLOWS:}
\]
\[
\text{Decrease_in_Connections} = \text{Attack} \cdot \text{Connections} \cdot \text{Damage_per_attack}
\]

\[
\text{Critical_Hubs}(t) = \text{Critical_Hubs}(t - dt) + (\text{Increase_in_Hubs} - \text{Decrease_in_Hubs}) \cdot dt
\]
\[
\text{INIT} \quad \text{Critical_Hubs} = \text{Initial_Hubs}
\]
\[
\text{INFLOWS:}
\]
\[
\text{Increase_in_Hubs} = \text{Effect_of_Clustering_on_Critical_Hubs}
\]
\[
\text{OUTFLOWS:}
\]
\[
\text{Decrease_in_Hubs} = \text{IF} (\text{Critical_Hubs} \geq \text{Maximum_Critical_Hubs}) \text{THEN} \text{IF} (\text{Critical_Hubs} \leq \text{Maximum_Critical_Hubs}) \text{ELSE}
\]
\[
\text{(Hub_Attack} \cdot \text{Hub_Damage})
\]

\[
\text{Efficiency}(t) = \text{Efficiency}(t - dt) + (\text{Change_in_Efficiency}) \cdot dt
\]
\[
\text{INIT} \quad \text{Efficiency} = \text{Initial_Efficiency}
\]
\[
\text{OUTFLOWS:}
\]
\[
\text{Change_in_Efficiency} = \text{IF}(\text{Efficiency} \geq 1) \text{THEN} (\text{Efficiency} - 1) \text{ELSE}
\]
\[
\text{Efficiency} \cdot (\text{Net_Effect})
\]

\[
\text{Nodes}(t) = \text{Nodes}(t - dt) + (\text{Increase_in_Nodes} - \text{Decrease_in_Nodes}) \cdot dt
\]
\[
\text{INIT} \quad \text{Nodes} = \text{Initial_Nodes}
\]
\[
\text{INFLOWS:}
\]
\[
\text{Increase_in_Nodes} = \text{Nodes} \cdot \text{Node_Growth}
\]
\[
\text{OUTFLOWS:}
\]
\[
\text{Decrease_in_Nodes} = \text{Nodes} \cdot \text{Attack} \cdot \text{Damage_per_attack}
\]
New Mobility Hub Networks and Rebound Effects

Purpose of the Model

The goal of this model is to evaluate the potential rebound effects the reduction in motorized transportation costs and travel time through implementing an integrated multimodal transportation, often referred to as a new mobility hub network.

A new mobility hub network is a network of hubs which provide just in-time transportation and access of a variety of transportation modes (ex. subway, taxis, cars, and buses). It is hypothesized that a new mobility hub network would reduce congestion, through encouraging ride sharing or use of public transit, reduce the need for motorized trips through encouraging urban design centered around key hubs which reduces travel time, and increasing accessibility to underserved populations through making transportation more affordable.

While the hypothesized benefits of a new mobility hub network are promising, there is potential for the savings from the hub network to be reinvested into travel, thereby returning congestion to its original state. This is often referred to as a rebound effect. A rebound effect is an extension of the law of demand that assumes that a certain percentage of savings will be reinvested into the task at hand, thereby increasing consumption. This trend has been specifically noted in the field of energy efficiency and transportation. For example, increased vehicle fuel economy often leads to an increase in vehicle miles traveled. Roadway expansion also has been shown to induce vehicle travel, quickly eliminating the short term benefits of reduced congestion. For this model, we applied the concept of the rebound effect to the application of a mobility network in an urban environment in the developing world. We have chosen a thirty year period as our time frame for this model assuming that the hub network was implemented today. The model uses data for Bangalore, India as the basis for the model, a city facing serious congestion issues with many roads currently with a congestion index greater than 1 during peak travel times as well as a large latent demand for transportation due to a large portion of the population living in poverty. The core question we seek to answer is how a new mobility hub network will impact congestion in the short and long run given potential rebound effects.

Model Definition and Key Variables

Our model is made up for four major sections:

- Cost per passenger trip – The sum of the cost per trip to the individual plus transportation subsidies provided by the government.
- Time per passenger trips – The average time per trip in minutes

---

• System capacity – the maximum number of passenger trips per year given the current transportation infrastructure.

• Number of passenger trips - number of passenger trips per year.

Additionally, we have two key modifiers to the system to test the concept of the hub network efficiencies and the potential rebound effect as a result of the increased efficiencies.

• Hub network efficiencies
  - Hub network cost efficiencies – Percent passenger trip cost reduction due to hub network efficiencies
  - Hub network time efficiencies – Percent passenger trip time reduction due to hub network efficiencies

• Rebound Effect
  - Percent cost savings reinvested – Percent cost savings reinvested based on a review of empirical findings on transportation related rebound effects
  - Percent time reinvested – Percent of time reinvested not to exceed time threshold for travel per day

The following table outlines the model’s variables and their relationships.

<table>
<thead>
<tr>
<th>Key Variable (include units)</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Income (USD)</td>
<td>The average income of a user in the system. This is modified by the Growth in Income variable</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td>Income Growth (%)</td>
<td>The flow that modifies Average Income.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Growth in Income (%)</td>
<td>The percent that the Average Income grows per year.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Government Subsidies (%)</td>
<td>The amount of money the government subsidizes the transportation network on a per trip basis. This is driven by a ratio of</td>
<td>Endogenous</td>
<td>Converter</td>
<td>X</td>
</tr>
</tbody>
</table>
cost per trip to average income that is then compared to society’s willingness to pay. The specific size of the subsidy is determined by the Percent Government Subsidy variable.

| Fractional Income Spent on Transport (%) | The maximum amount of an average person’s income that can acceptably be spent on transportation. The assumption is that if they have to spend more than this amount they will force the government to subsidize transportation. | Exogenous | Converter |
| Percent Government Subsidy (%) | The size of the government subsidy as a percentage of the cost per trip. | Exogenous | Converter | X |
| Hub Network Cost Efficiencies (%) | This is the amount of cost savings a new mobility hub network can give a transportation system. It is a variable that is expressed as a percentage of cost per trip. | Endogenous | Converter | X |
| Cost (USD) | Cost per trip in the transportation system. This is modified by Inflation, Congestion Factor, Government Subsidies and Hub Network Cost Efficiencies. | Endogenous | Stock | X |
| Increases in Cost (USD) | The amount in one unit time that the cost increases. This is modified by Inflation and the Congestion Factor. | Endogenous | Flow |
| Decreases in Cost (USD) | The amount in one unit time that the cost decreases. This is modified by Government Subsidies and Hub Network Cost Efficiencies. | Endogenous | Flow |
| Cost Savings Reinvested (USD) | This is the amount of the cost that is saved in the year to year changes in cost that is used to purchase additional trips in the system. This is modified by Increases in Cost, Decreases in Cost and Percent Cost | Endogenous | Converter |
Percent Cost Reinvested (%) | This is the fraction of the cost savings that is spent on additional trips in the system. | Exogenous | Converter

### Time per Trip

<table>
<thead>
<tr>
<th>Key Variable</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time per Trip (min)</td>
<td>This is the average amount of time that it takes to complete an average trip in the system. This is modified by Hub Network Time Efficiencies, and the Congestion Factor.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td>Increase in Time (min)</td>
<td>This is the increase in the amount of time an average trip in the system takes. This is modified by the Congestion Factor.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Decrease in Time (min)</td>
<td>This is the increase in the amount of time an average trip in the system takes. This is modified by the Congestion Factor and Hub Network Time Efficiencies.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Hub Network Time Efficiencies (%)</td>
<td>This is the amount of time savings a new mobility hub network can give a transportation system. It is a variable that is expressed as a percentage of time per trip.</td>
<td>Endogenous</td>
<td>Converter</td>
<td>X</td>
</tr>
<tr>
<td>Time Savings Reinvested (min)</td>
<td>This is the amount of the time that is saved in the year to year changes in cost that is used to purchase additional trips in the system. This is modified by Increases in Time, Decreases in Time and Percent Time Reinvested.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Percent Time Reinvested (%)</td>
<td>This is the fraction of the time savings that is spent on additional trips in the system.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
</tbody>
</table>
## System Capacity

<table>
<thead>
<tr>
<th>Key Variable</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Capacity (trips)</td>
<td>This is the optimal number of trips that a system can handle without any increases in time or cost.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td>Planned Increase in Capacity (%)</td>
<td>The amount of transportation infrastructure that is being added to the system to deal with increased demand for trips. This is modified by Maximum Capacity, Time to Add Capacity, and Infrastructure Improvements.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Congestion Factor (dimensionless)</td>
<td>This is the ratio of the number of trip taken in a system to the system capacity.</td>
<td>Endogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Room for Capacity Improvement (dimensionless)</td>
<td>This is the ratio of the maximum capacity to the initial capacity. This is basically the room there is for the capacity to grow.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td>Infrastructure Improvements (dimensionless)</td>
<td>The amount of capacity that is to be added when additional capacity is added to the system. This is modified by the Congestion Factor, Threshold for Action, and Percent Infrastructure Improvement.</td>
<td>Endogenous</td>
<td>Converter</td>
<td>X</td>
</tr>
<tr>
<td>Percent Infrastructure Improvement (%)</td>
<td>The percentage of the current capacity that is added every time there is additional capacity added to the system.</td>
<td>Exogenous</td>
<td>Converter</td>
<td>X</td>
</tr>
<tr>
<td>Threshold for Action (dimensionless)</td>
<td>This is the trigger for the adding of additional infrastructure based on the congestion of the current system.</td>
<td>Exogenous</td>
<td>Converter</td>
<td>X</td>
</tr>
<tr>
<td>Time to Add Capacity</td>
<td>This is lag for the construction (addition) of additional infrastructure.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
</tbody>
</table>
### Maximum Capacity

This is the maximum optimal, assuming that all possible improvements are made, capacity of the transportation system.

<table>
<thead>
<tr>
<th>Key Variable (Unit)</th>
<th>Description</th>
<th>Endogenous/Exogenous</th>
<th>Stock/Flow/Converter</th>
<th>Policy Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trips</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trips (trips)</strong></td>
<td>The number of trips made in the system for a given year. This is modified by Time Savings Reinvested, Cost Savings Reinvested, Increase in Trips, Decrease in Trips, Cost Threshold, Time Threshold, and Present Decrease Due to Threshold.</td>
<td>Endogenous</td>
<td>Stock</td>
<td></td>
</tr>
<tr>
<td><strong>Increase in Trips (trips)</strong></td>
<td>This is the additional number of trips taken/required in the system. This is modified by Population Growth Rate, Time Savings Reinvested, Cost Savings Reinvested, Time per Trip, and Cost per Trip.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td><strong>Decrease in Trips (trips)</strong></td>
<td>This is the decrease in the number of trips taken in the system. This is modified by Cost Threshold, Time Threshold, Percent Decrease Due to Threshold, Time per Trip, and Cost per Trip.</td>
<td>Endogenous</td>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td><strong>Time Threshold (min)</strong></td>
<td>This is the limit to the amount of time that a person is willing accept for a trip.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Cost Threshold (USD)</strong></td>
<td>This is the limit to the amount of money that a person is willing to accept for a trip.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
<tr>
<td><strong>Percent Decrease Due to Threshold (%)</strong></td>
<td>This is the fraction of trips that decrease due to exceeding either the Cost Threshold or the Time Threshold.</td>
<td>Exogenous</td>
<td>Converter</td>
<td></td>
</tr>
</tbody>
</table>
Reference Behavior Pattern

The model we have constructed is a hypothesized model based on the implementation of a new mobility hub network that incorporates a rebound effect. The model assumes that a hub network is implemented today in Bangalore, India and the results are modeled over a thirty year time period. This model is compared to a base case where no hub network is implemented.

Basic Mechanisms and Organizing Principles

If a hub network is not implemented, we anticipate that time per trip and cost per trip will continue to rise and the number of trips will eventually revert to the bare minimum of trips necessary for society to function. This is because the trip time and cost will surpass the time and cost thresholds due to congestion.

We anticipate that the implementation of the new mobility hub network will postpone this impact and increase the potential number of trips per year; however, system capacity and time per trip will eventually reach the threshold.

The reasons for eventually reaching this threshold is due to continued population growth, a latent demand for travel, the rebound effect which assumes that a proportion of savings due to travel will be reinvested into more travel, and limits to infrastructure expansion.

Our dynamic hypothesis is that installing and using mobility hub networks lead to cost and time savings which can actually lead to more trips, and perhaps unexpected congestion, due to rebound effects.

Hub Network Time and Cost Efficiencies

Hub networks are believed to provide both time and cost efficiencies by reducing congestion through encouraging use of mass transit (reduction in vehicle miles traveled), urban design that increases accessibility and decreases the need for motorized travel, and reduced travel time through route optimization and timing of trips. While the exact sources of benefits and percentages cannot be known precisely without a specific design, it is assumed that the new system will decrease the travel time and costs. However, there are limits to time and cost efficiencies that a hub network can provide. In our model, we have assumed that additional improvement to the hub network will be zero by year fifteen. Figure 1 and Figure 2 show the model for efficiencies included in our model.
Rebound Effect

According to M. Binswanger’s review of empirical studies of the rebound effect with respect to energy efficient technology, 5-50% of energy savings is invested in additional consumption of the good or service (Binswanger, 2001, p. 123). Studies reviewed related to vehicle miles traveled with respect to fuel economy experienced rebound effects ranging from 9%-22%.² For this paper, we ran three scenarios of

cost savings reinvested in transportation, 5%, 25%, and 50% to study the sensitivity of the rebound effect on time traveled, number of trips, and cost per trip.\(^3\)

**Causal Loop Diagram**

The passenger trips to congestion, to passenger trip cost is a balancing loop. The trip time to passenger trips to congestion, to trip time also is a balancing loop. It is hypothesized that there is a limit to the capacity of the system and the hub network provides a short term fix but addresses symptomatic issues of congestion rather than fundamental problems of accessibility for all. Additionally, it is predicted that congestion will oscillate over time as changes in trip time and trip cost influence the number of passenger trips per year.

\(^3\) There are two other key variables that must be taken into account when considering the rebound effect: Substitutability between services and the income effect. Substitutability is substituting one mode of transportation for another (non-motorized vs. motorized) and income effect is investing the money saved into the purchase of other goods and services rather than investing it back into transportation. A lower rebound effect would assume a greater income effect and substitutability whereas a higher rebound effect assumes a lower income effect and substitutability (Binswanger, M. 2000).
Parameter Values

In setting our base variable values, we used Bangalore, India as a reference point. For the variables that do not have hard data, especially the effect that hub networks can have on the cost and time required for transportation, we have used graphs that clearly show our assumptions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Assumption/Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth in Income</td>
<td>Assumed to be 8.7%. Based on the general economic growth of Bangalore from 2005-06. Source: <a href="http://www.hinduonnet.com/2006/03/21/stories/2006032109900400.htm">http://www.hinduonnet.com/2006/03/21/stories/2006032109900400.htm</a></td>
</tr>
<tr>
<td>Hours Worked per Year</td>
<td>2080. Assuming a standard 40 hour and 5 day work week.</td>
</tr>
<tr>
<td>Average Income</td>
<td>Assumed to grow at a steady rate (Growth in Income). For simplicity, average income never decreases.</td>
</tr>
<tr>
<td>Fractional Income Spent on</td>
<td>22%. Assuming that a person in Bangalore uses transportation at the same rate of a person with similar income in the US. Source: [<a href="http://www.bts.gov/publications/issue_briefs/number_01/html/commuting_expen">http://www.bts.gov/publications/issue_briefs/number_01/html/commuting_expen</a> ses_disparity_for_the_working_poor.html](<a href="http://www.bts.gov/publications/issue_briefs/number_01/html/commuting_expen">http://www.bts.gov/publications/issue_briefs/number_01/html/commuting_expen</a> ses_disparity_for_the_working_poor.html)</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td>Percent Government Subsidy</td>
<td>2%. This assumption is based on a rough average of the yearly change (ranges from 0 to 5%) in the Indian government’s subsidy of the public bus service in Mumbai. Source: <a href="http://siteresources.worldbank.org/INTTRANSPORT/Resources/336291-1171658979314/3465102-1175712481687/Mumbai_Transit_SHORT_REV.pdf">http://siteresources.worldbank.org/INTTRANSPORT/Resources/336291-1171658979314/3465102-1175712481687/Mumbai_Transit_SHORT_REV.pdf</a></td>
</tr>
<tr>
<td>Cost per Trip</td>
<td>See Initial Cost per Trip for the basis of the initial value. Future values are calculated based on the input of Increases in Cost and Decreases in Cost.</td>
</tr>
<tr>
<td>Inflation</td>
<td>5.3%. Assuming that the current inflation rate will be steady over the course of the simulation. Source:</td>
</tr>
<tr>
<td>Table 1: Assumptions</td>
<td>Assumptions/Base Case</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Increases in Cost</td>
<td>Assumed to increase with inflation and as the congestion factor exceeds the Inefficient Cost Congestion Factor.</td>
</tr>
<tr>
<td>Inefficient Cost</td>
<td>1.5. This is the level of congestion that will lead to cost inefficiencies. This value is a pure assumption.</td>
</tr>
<tr>
<td>Congestion Factor</td>
<td></td>
</tr>
<tr>
<td>Decreases in Cost</td>
<td>Assumed to decrease with government subsidies and the benefits of a hub network.</td>
</tr>
<tr>
<td>Percent Cost</td>
<td>25%. Based on an average of expert opinions. Source:</td>
</tr>
<tr>
<td>Reinvested</td>
<td></td>
</tr>
<tr>
<td>Cost Savings</td>
<td>Assumed to be the fraction of cost that is saved per trip that is reinvested to create new trips.</td>
</tr>
<tr>
<td>Reinvested</td>
<td></td>
</tr>
<tr>
<td>Hub Network</td>
<td>This is the assumed cost efficiencies of the hub network system. In the model this is a graph so that we can properly estimate is effect throughout the life of the model. This assumption is based only on our collective opinions.</td>
</tr>
<tr>
<td>Cost Efficiencies</td>
<td></td>
</tr>
</tbody>
</table>

### Time per Trip

<table>
<thead>
<tr>
<th>Variable</th>
<th>Assumption/Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time per Trip</td>
<td>See Initial Time per Trip for the basis of the initial value. Future values are calculated based on the input of Increase in Time and Decrease in Time.</td>
</tr>
<tr>
<td>Increase in Time</td>
<td>Assumed to increase if the congestion of the system increases.</td>
</tr>
<tr>
<td>Decrease in Time</td>
<td>Assumed to decrease if the congestion of the system decreases or if the hub network improves the efficiency of the system.</td>
</tr>
<tr>
<td>Hub Network</td>
<td>This is the assumed time efficiencies of the hub network system. In the model this is a graph so that we can properly estimate is effect throughout the life of the model. This assumption is based only on our collective opinions.</td>
</tr>
<tr>
<td>Time Efficiencies</td>
<td></td>
</tr>
</tbody>
</table>
Percent Time Reinvested | 100%. According to World Business Council on Sustainable Development, the time spent traveling per person per day remains at an average of 1 hr throughout the world. While distant traveled changes, the amount of time remains relatively constant. For this reason, percent of time reinvested in travel is 100%.

Time Savings Reinvested | Assumed to be the fraction of time that is saved per trip that is reinvested to create new trips.

### System Capacity

<table>
<thead>
<tr>
<th>Variable</th>
<th>Assumption/Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room for Capacity Improvement</td>
<td>4. This number is an assumption because they have very poor infrastructure. We tried to compare the length of roads and subways (741 km for Bangalore) to the overall footprint of the city (4300 km²) and then compare that to a city that has good infrastructure like New York City to see if the ratio would be much higher (the ratio for NYC is 6.13 for Bangalore it is 5.8), but we feel this difference is too small to totally grasp the scope of possible improvements. Source: <a href="http://en.wikipedia.org/wiki/Bangalore">http://en.wikipedia.org/wiki/Bangalore</a> and <a href="http://en.wikipedia.org/wiki/New_York_City">http://en.wikipedia.org/wiki/New_York_City</a></td>
</tr>
<tr>
<td>Infrastructure Improvements</td>
<td>Assumed to increase by the Percent Infrastructure Improvement only after the Congestion Factor is greater than the Threshold for Action.</td>
</tr>
<tr>
<td>Maximum Capacity</td>
<td>Assumed to be the existing optimal capacity multiplied by the Room for Capacity Improvement.</td>
</tr>
<tr>
<td>Time to Add Capacity</td>
<td>2 years. Rough estimate as time to add capacity because the time will vary depending on the type of capacity added.</td>
</tr>
<tr>
<td>Percent Infrastructure Improvement</td>
<td>15%. This is an assumption.</td>
</tr>
<tr>
<td>Planned Increase in Capacity</td>
<td>Assumed to be a time lagged amount of capacity that is added to the system that will not allow the System Capacity become greater than the Maximum Capacity.</td>
</tr>
</tbody>
</table>
System Capacity | The initial optimal capacity of the system. It is assumed to be the product of the StartingPop, YearlyTrips, PercentMotorizedTrips divided by the Initial Congestion Factor. It increases with Planned Increase in Capacity.
---|---
Congestion Factor | Assumed to be the ratio of Trips to System Capacity.

<table>
<thead>
<tr>
<th>Trips</th>
<th>Assumption/Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Time Threshold</td>
<td>90 minutes. According to World Business Council on Sustainable Development, the time spent traveling per person per day remains at an average of 1 hr throughout the world. While distant traveled changes, the amount of time remains relatively constant. For this reason, the maximum time allotted time to travel is set at 90 min. Source: World Business Council for Sustainable Development (WBCSD). 2001. Mobility 2001: World Mobility at the End of the Twentieth Century.</td>
</tr>
<tr>
<td>Percent Decrease Due to Threshold</td>
<td>10%. This is an assumption.</td>
</tr>
<tr>
<td>Cost Threshold</td>
<td>$3. This is an assumption based on the fact that this cost would be about 50% of the average income.</td>
</tr>
<tr>
<td>Population</td>
<td>Assumed to grow and never decrease. Its initial value is StartingPop. It will increase with Population Growth.</td>
</tr>
<tr>
<td>Population Growth</td>
<td>The fractional increase to population based on the Population Growth Rate.</td>
</tr>
<tr>
<td>YearlyTrips</td>
<td>365. We assume that each person using the system would take on average one trip</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Trips</td>
<td>Initial number of trips assumed to be the product of StartingPop, YearlyTrips, PercentMotorizedTrips. The number of trips is then increased or decreased by Increase in Trips and Decrease in Trips.</td>
</tr>
<tr>
<td>Increase in Trips</td>
<td>Assumed to minimally increase at the Population Growth Rate. It could also grow with the input from Cost Savings Reinvested and Time Savings Reinvested.</td>
</tr>
<tr>
<td>Decrease in Trips</td>
<td>Assumed to decrease if the cost or time thresholds are exceeded.</td>
</tr>
</tbody>
</table>

**Test Dynamic Hypothesis**

**Base Case**

As mentioned above, we first used the model to examine the base case. For our base case, all variables are at their given values in the table above, but there is no hub network installed. Therefore, both Hub Network Cost Efficiencies and Hub Network Time Efficiencies give no benefits to the transportation system. Figure 4 is a graph outputted by the model. Note that there is a drop in the number of trip around year 13 that is due to the fact that the Time per Trip is greater than the Time Threshold. The only reason that the number of trips does not continue to go down after year 14 is the latent demand of the population for minimal transportation. As you can see this high demand coupled with lower than necessary System Capacity leads to high Cost per Trip due to great inefficiencies.
Hub Network Effects

Next, we examined the effects that a new mobility hub network could have on our transportation system. Figure 5 is the output graph from the model to demonstrate the hub network effect. Note that here the costs for the system remain much lower than the base case. It is also important to note that the hub network was able to delay a drop in Trips due to the Time per Trip being greater than the Time Threshold until year 20. This is a 7 year improvement. Since the slope of the Trips line in Figure 5 is greater than the slope of the Trips line in Figure 4, the hub network drives an increased demand for Trips. The increase demand is most likely caused by a rebound effect due to the cost and time savings.

---

4 We assumed that the hub network would have a positive effect on the system for at least 15 years, but after that we are assuming that it adds no additional benefit.
Sensitivities and Policy Levers

Next we were interested in checking how sensitive our model was to changes in a select number of variables. We have tried to focus on the variables that will help prove our dynamic hypothesis that there is a rebound effect in transportation. We also wanted to look at the variables that the government, the transportation policy makers, can control. The variables that we looked at are:

1. Percent Cost Savings Reinvested
2. Percent Time Savings Reinvested
3. Percent Government Subsidy
4. Percent Infrastructure Improvement

For Percent Cost Savings Reinvested, we looked at varying the value from 5% to 25% to 50%. Figure 5 shows the output of the model with 25% Cost Savings Reinvested. When we ran the model with Percent Cost Savings Reinvested at 5% and 50% we got very similar graphs. Upon further inspection, since the actual cost savings taking place is a small fraction of the Cost per Trip, even if 100% of it is reinvested it leads to a small number of increased trips. In order to see if there would be a rebound effect if there was a greater constant cost savings, giving more funds for reinvestment, the Hub Network Cost Efficiencies was set to 15% for the entire 30 year run of the model. Figure 6 is the output when Percent
Cost Savings Reinvested is set to 5%. Figure 7 is the output when Cost Savings Reinvested set to 25%. Figure 8 is the output when Percent Cost Savings Reinvested is set to 50%.

It is interesting to note that in each of these figures you can see a rebound effect. More trips are taken when money is saved, and it becomes more pronounced as the amount of reinvestment increases. The drop in Trips in each of the figures is due to the congestion in the system growing, driving the Time per Trip up to a point that it is no longer tolerable for the user. Therefore, our model under normal operating conditions is not sensitive to Cost Savings Reinvested. But it is sensitive when there is a constant cost savings throughout the life of the model.
The sensitivity of the model to Time Savings Reinvested is quite similar to that of Cost Savings Reinvested. Under normal operating conditions, there is no noticeable change in the output if the Time...
Savings Reinvested is set to 0% or 100%. But again, if there is a constant time savings of 15%, setting Hub Network Time Efficiencies to 15% for the 30 years of the model, you can see the rebound effect. Figure 9 and Figure 10 show this behavior for a Time Savings Reinvested of 50% and 100% respectively. The interesting thing to note here is that the model is more sensitive to Time Savings Reinvested than Cost Savings Reinvested. This is shown because the rate at which Trips is increasing is greater.

Figure 9 Output from Model with Constant 15% Time Savings and a Reinvestment Rate of 50%
A sensitivity analysis was run on Percent Government Subsidy because it is a policy lever that the government could use to change Cost per Trip. To determine how sensitive the model is to Percent Government Subsidy its value was varied from 0% to 50%. Figure 11 through Figure 13 show the output from the model for 0%, 25% and 50% Percent Government Subsidy respectively. It is interesting to note that the final number of Trips does not change based on the amount of subsidy, just the shape of the Trips line. This is because the subsidy lowers the Cost per Trip to such a low level the first time it is introduced that the government never has to introduce another one. Because of this I would say that this model is fairly insensitive to the Percent Government Subsidy in the long term, but it could be used as a policy level to decrease the Cost per Trip thus increasing the number of Trips in the short term.
Figure 11 Output Graph for the Model with 0% Government Subsidies

Figure 12 Output Graph for the Model with 25% Government Subsidies
Percent Infrastructure Improvement was subject to a sensitivity analysis because it is a policy lever for the government to deal with mobility. If congestion is consistently high in an area, the government may choose to increase the amount of infrastructure that they add at any given time. If Percent Infrastructure Improvement is varied from 5% to 30% to 55%, it is clear that it has an impact on all of the output. Figure 14 through Figure 16 show this behavior. It will drive the number of trips up and smooth out the curve so people are always taking more trips. It will also drive Cost per Trip and Time per Trip down since it lowers congestion in the system. Of course, it is most likely not feasible to add an additional 55% of capacity into an existing transportation system with huge capital expenditures that most government are unwilling or unable to make.
Figure 14 Output Graph for the Model with 5% Infrastructure Improvement

Figure 15 Output Graph for the Model with 30% Infrastructure Improvement
Ways to Improve the Model

There are a number of ways the model could be improved to be more accurate. First, this model assumes that cost and price are synonymous and that all rides are subsidized by the government given certain conditions. Secondly, the model is based on average income per capita rather than modeling the classifying the population into different income brackets and modeling their amount of ridership. Cost per trip could be enhanced by including the cost of fuel overtime. Increase in trips could be influenced by income growth. The congestion could impact the overall economy of the region including population growth and income per capita thus influencing ridership. And the hub network and system capacities could be enhanced by including vehicle types, average ridership, queue length, congestion hours, and wait times to more accurately reflect the changes in the system.
Appendix A – Stella Equations

Stocks and Flows

- \( \text{Average Income}(t) = \text{Average Income}(t - dt) + (\text{Income Growth}) \times dt \)
  
  INIT: \( \text{Average Income} = \text{Initial Average Income} / \text{Hours Worked per Year} \)
  
  INFLOWS:
  - \( \text{Income Growth} = \text{Average Income} \times (\text{Growth in Income}) \)

- \( \text{Cost per Trip}(t) = \text{Cost per Trip}(t - dt) + (\text{Increases in Cost} - \text{Decreases in Cost}) \times dt \)
  
  INIT: \( \text{Cost per Trip} = \text{Initial Cost Per Trip} \)
  
  INFLOWS:
  - \( \text{Increases in Cost} = \text{If} (\text{Congestion Factor} > \text{Inefficient Cost Congestion Factor}) \text{THEN} \)
    \( \text{Cost per Trip} \times (\text{Inflation} \times (\text{Congestion Factor} \times \text{Inefficient Cost Congestion Factor})) \text{ELSE} \)
    \( \text{Cost per Trip} \times (\text{Inflation}) \)
  
  OUTFLOWS:
  - \( \text{Decreases in Cost} = \text{Cost per Trip} \times (\text{Hub Network Cost Efficiencies} + \text{Government Subsidies}) \)

- \( \text{Population}(t) = \text{Population}(t - dt) + (\text{Population Growth}) \times dt \)
  
  INIT: \( \text{Population} = \text{Starting Pop} \)
  
  INFLOWS:
  - \( \text{Population Growth} = \text{Population Growth Rate} \times \text{Population} \)

- \( \text{System Capacity}(t) = \text{System Capacity}(t - dt) + (\text{Planned Increase in Capacity}) \times dt \)
  
  INIT: \( \text{System Capacity} = \text{Starting Pop} \times \text{Yearly Trips} \times \text{Percent Motorized Trips} / \text{Initial Congestion Factor} \)
  
  INFLOWS:
  - \( \text{Planned Increase in Capacity} = \text{If} (\text{System Capacity} > \text{Maximum Capacity}) \text{THEN} 0 \text{ELSE} \)
    \( \text{System Capacity} \times \text{Infrastructure Improvements} / \text{Time to Add Capacity} \)

- \( \text{Time per Trip}(t) = \text{Time per Trip}(t - dt) + (\text{Increase in Time} - \text{Decrease in Time}) \times dt \)
  
  INIT: \( \text{Time per Trip} = \text{Initial Time per Trip} \)
  
  INFLOWS:
  - \( \text{Increase in Time} = \text{If} (\text{Congestion Factor} > \text{Initial Congestion Factor}) \text{THEN} \)
    \( \text{Time per Trip} \times (\text{Congestion Factor} - \text{Initial Congestion Factor}) \text{ELSE} 0 \)
  
  OUTFLOWS:
  - \( \text{Decrease in Time} = \text{If} (\text{Congestion Factor} < 1) \text{THEN} \)
    \( \text{Time per Trip} \times (\text{Hub Network Time Efficiencies}) \text{ELSE} \)
    \( \text{Time per Trip} \times \text{Hub Network Time Efficiencies} \)

- \( \text{Trips}(t) = \text{Trips}(t - dt) + (\text{Increase in Trips} - \text{Decrease in Trips}) \times dt \)
  
  INIT: \( \text{Trips} = \text{Percent Motorized Trips} \times \text{Starting Pop} \times \text{Yearly Trips} \)
  
  INFLOWS:
  - \( \text{Increase in Trips} = \text{If} (\text{Trips} \geq (\text{Population} \times \text{Yearly Trips} \times \text{Percent Motorized Trips})) \text{THEN} \)
    \( \text{Cost Savings Reinvested} \times (\text{Cost Savings Reinvested} \times \text{Population Growth Rate}) \text{ELSE} \)
    \( \text{Population} \times \text{Yearly Trips} \times \text{Percent Motorized Trips} \)
  
  OUTFLOWS:
  - \( \text{Decrease in Trips} = \text{If} (\text{Cost per Trip} > \text{Cost Threshold}) \text{OR} (\text{Time per Trip} > \text{Time Threshold}) \text{THEN} \)
    \( \text{Trips} \times \text{Percent Decrease Due to Threshold} \text{ELSE} 0 \)
Converters

- Congestion_Factor = Trips/System_Capacity
- Cost_Savings_Reinvested = IF(Decreases_in_Cost < Increases_in_Cost) THEN 0 ELSE ((Decreases_in_Cost - Increases_in_Cost)/Cost_per_Trip)*Trips)*Percent_Cost_Reinvested
- Cost_Threshold = 3
- Fractional_Income_Spent_on_Transport = .3
- Government_Subsidies = IF(Cost_per_Trip(Average_Income*(Time_per_Trip/60))>Fractional_Income_Spent_on_Transport) THEN Percent_Government_Subsidy ELSE 0
- Growth_in_Income = 0.087
- Hours_Worked_per_Year = 2080
- Inefficient_Cost_Congestion_Factor = 1.5
- Inflation = .03
- Infrastructure_Improvements = IF(Congestion_Factor>=Threshold_for_Action) THEN Percent_Infrastructure_Improvement ELSE 0
- Initial_Average_Income = 22000
- Initial_Congestion_Factor = 1.4
- Initial_Cost_Per_Trip = 1.53
- Initial_Time_per_Trip = 42
- Maximum_Capacity = StartingPop*PercentMotorizedTrips*YearlyTrips*Room_for_Capacity_Improvement
- PercentMotorizedTrips = .85
- Percent_Cost_Reinvested = .25
- Percent_Decrease_Due_to_Threshold = .1
- Percent_Government_Subsidy = .02
- Percent_Infrastructure_Improvement = .15
- Percent_Time_Reinvested = 1
- Population_Growth_Rate = 0.0274
- Room_for_Capacity_Improvement = 4
- StartingPop = 5.7
- Threshold_for_Action = 1.5
- Time_Savings_Reinvested = IF(Decrease_in_Time>Increase_in_Time) THEN ((Decrease_in_Time - Increase_in_Time)/Time_per_Trip)*Percent_Time_Reinvested*Trips Else 0
- Time_Threshold = 90
- Time_to_Add_Capacity = 2
- YearlyTrips = 365

Hub_Network_Cost_Efficiencies = GRAPH(TIME)

Hub_Network_Time_Efficiencies = GRAPH(TIME)
Observations on the nature of “innovation” and its social context.

The word “innovation” appears in discussions of nearly every kind of societal problem, especially ones having to do with new technology. Whatever the problem, “innovation” is the solution and, incidentally, the foundation for new entrepreneurial businesses and economic growth. “Innovation” has almost become a cliché. Nevertheless, despite the trendiness of “innovation”, there is a huge body of scholarly literature on innovation as the explanation for economic growth, what it means, and how it happens (Baumol, 2002). Running through this literature are recurrent discussions about the definition of “innovation” and the formulation of a conceptual framework for what it is and how it is done. Many of the theoretical problems with the definition can be somewhat vague and slippery, but generally the discussions fall back on a contextual definition: we think we know it when we see it.

In thinking about innovation for New Mobility and urban-transportation, context is especially relevant because the domain has a large and diverse set of stakeholders distributed across nations, each with their own perspectives about innovation. In the context of New Mobility, the “buzz” is around new features and services associated with wireless communication, the internet, various computer-aided devices, or other computer-
based technological-centric innovations. We should not, however, equate “innovation” with specific technologies. While there is comfort in the specificity of concrete technological examples, we should also recognize that “innovation”, New Mobility, entrepreneurialism, New Economy, etc are powerful motivational symbols, and this motivational value can be enhanced by building a framework that leads to actionable outcomes. Despite the theoretical problems, the innovation literature yields some generalizations that are useful guidelines for thinking about specific practical situations.

The purpose of this paper is to call attention to some generalizations that may help the urban-mobility communities find common ground for thinking together about innovation and searching for entrepreneurial opportunities.

One conclusion from the scholarly literature is that technological innovation is always accompanied by a social process through which the innovations become accepted by the eventual end-users (Nye, 2002, Hughes, 2004, Baumol, 2002). Succinctly put: technologies provide alternatives, but people choose. Thus the acceptance of innovative technologies is context dependent, path dependent, and laden with consumer choices that are likely to depend on culture. While the urban transportation problems from around the world have many common physical features, such as congestion and infrastructural requirements, local cultural preferences may determine practical implementation of solutions. It is therefore critical to keep in mind that what is true in New York City may be irrelevant to “New City” in Asia, Africa, or South America. The social history of technology provides many examples of how local cultures and people shape the evolution of technologies. (Nye, 2002).
As one illustration of the importance of social-context, we call attention to the social-history of electric lighting and the evolution of cities. The history of electrification makes a strong case that the emergence of lighting was a main technological driver of the growth and development of US and European cities, but the way in which people responded to urban lighting was different in many ways in Europe and the U.S. (Nye, 1990). Another illustration, more specific to urban transportation, is automobile history. The list of “innovations” is long, but ones with a prominent social context would include: gas stations, motels, highways, car-servicing, drive-through restaurants, parking-for-profit, car-racing as entertainment, liability insurance, drivers’ licensing, and automobile registration. All of these were innovations of their times, most had technological components, but their growth and acceptance depended on how people used and accepted them.

The lesson from the social-history of innovation for the urban-transportation (New Mobility) community is that people matter as much as, or maybe more than, the technologies. In the quest for solutions to urban-transportation problems, the community needs to keep a sharp eye on people-problems, rather than on the specific merits of technologies.

**Observations on innovation and entrepreneurs: five rules from MBA professors.**

Innovation is not just “invention”; it requires pathways to implementation and practical application. Implementation of innovation has almost always (at least in the US and Western Europe) occurred through the agency of entrepreneurs—the financial and business risk-takers who launched new enterprises (Baumol, 2002). The scholarly literature on entrepreneurs has much in common with the innovation literature in its
definitional complexities and context-dependence, but over the years MBA educators have extracted a useful framework for entrepreneurs built around five questions: Who are the customers? What is the product? How are we going to make it? How are we going to sell it? How are we going to profit? Clearly, these five questions are linked to each other, but the starting point is Who. In the domain of urban transportation, customers can be seen as any of the stakeholders, for example regional transportation authorities, equipment manufacturers, service providers, governments, policy-makers, etc, but the history of innovation strongly suggests that the primary “Who” are the users of the urban transportation services. These users are ME and YOU, and the New Mobility community needs to observe us as anthropologists would in order to understand what our real problems are. Innovations may be needed to deal with problems of aesthetics, safety, and security rather than sleek trains and cell-phones. WE, the users, may be an important source of innovation, provided the urban-transportation stakeholders can create a path for acceptance. The notion that WE, as end-users, can be innovators is old and has been examined comprehensively in the work of von Hipple (2003).

Observations on transportation invariants: time, money, choice, crowds.

In seeking opportunities for future urban-mobility innovations, despite the diversity of cultures and place, there are certain invariants regardless of context. Four invariants are: time budgets, money budgets; the option to go whenever and wherever; and congestion.

The first of these invariants—people’s travel-time budget—emerges from empirical studies (Schaefer, 1998, Schaefer and Victor, 2000) that show, on rough
average, that people spend more or less an hour/day traveling to and from destinations, and that this “travel-time-budget” is roughly a behavioral invariant that can be observed historically over many hundreds of years and in communities as diverse as villages in “primitive” hunter-gatherer societies and the modern age of automobile commuters.

The second of the invariants is people’s money budgets. In the U.S. the distribution of household money-budgets spent on travel peaks around 15% of total household budgets.

These time and money “invariants” are constraints on innovation: no innovation will be effective if it requires people to exceed these budgets. Moreover, proposed innovations predicated on assumptions of substantial future expansion of travel-time or household money budgets are not likely to be accepted, regardless of their technological prowess. People are not going to spend more time per day or more money traveling—except possibly over period in response to perturbations such as sharp changes in fuel prices.

The third invariant comes from the history of the automobile. Historians have concluded, rather widely, that the single most important attribute of automobiles is that they enable people to have the option of going wherever and whenever they want to. This option is deeply entrenched in our modern behaviors, we are willing to spend a substantial portion of our income to get it, and it is manifested in our use and ownership of cars and in the evolution of suburbs and cities. Any solutions to urban mobility problems that encroach on this optionality will have to offer powerful incentives if people are to accept them.
The fourth invariant for comment has to do with congestion. While congestion is universally seen as undesirable and unpleasant, it is an unavoidable consequence of the coincidence of demand in time for a particular location—everyone wants to be in the same place at the same time. Investments in mitigating congestion may be futile (Downs, 2004), and a better innovative approach may be to understand congestion as a transaction cost that people are willing to incur, and the challenge is to figure out how to make congestion livable—Disney World has figured out how.

**Observations on where innovation comes from.**

It is one thing to aspire to “innovative” solutions and another to make them happen. Despite the vast scholarly literature on the origins of innovation in its diverse contexts, no one really understands how it happens, except in the very general way that it is a social process and path dependent. Path dependence essentially captures the idea that “today” has behind it a long history of choices and actions from many sources, and it is impossible to trace in any causal and unambiguous way how we got to where we are. There are, however, some generalizations that run through the literature, ones that are not widely appreciated even by those who call out for “innovative” solutions to any problem.

One generalization is that innovation is a “deep craft”. It is a full-time activity of “innovators” and not a part-time finger exercise for dilettantes. Innovation cannot be created by fiat, and as the biographies of the great innovators show (Hughes, 2004), failure is the rule rather than the exception. In the community of innovators, failure is a virtue. Silicon Valley folk lore tells us that a venture capitalist who has not failed several times is not worth his salt. Thus, if the community working on urban mobility problems
seeks to exploit the power of innovation, it needs to create a community in which all of the time-tested understanding of the innovator’s culture needs to be recognized and fostered.

For innovation to succeed, innovators, entrepreneurs, and all of the stakeholders must pay due respect to the conservative power of vested interests. Change implied by innovation typically runs counter to the interests of established stakeholders, and the paths to incorporating innovative solutions may face difficult-to-surmount obstacles. In the language of recent advances in behavioral economics, the *endowment effect* (Kahneman and Knetsch, 1992) is a powerful antagonist to change—we don’t easily give up what we already have.

Innovation, as Christensen has observed (Christensen, 1995), is more than the steady perfection and improvement of existing products—so called incremental change. Christensen describes famous examples of great companies that went out of business because of the appearance of a so-called disruptive innovation from outside of the companies. The lesson for the New Mobility community is that they may be so close to the problems that they may not see opportunities that could arise from outside of their domain. One example of such an “outsider’s” creation might be Zipcar.

The general observation that adoption of innovation is a social process has an important consequence. The technically “best” solution may not be the solution that becomes adopted. The reason is that feedbacks in the marketplace influence customers’ choices. A technology that gets an early foothold may create a public perception of preference, and subsequent buyers are influenced by the choices already made by previous buyers. This phenomenon, called increasing returns to adoption, may
profoundly affect the path of adoption. An often cited example is the mid 1970’s early
1980s competition between VHS and Beta video tape formats; the VHS format
eventually won, although the technical community considered the Beta format superior.
The end-users decided the winner, and not necessarily on rational technical grounds
(Arthur, 1989; Arthur, 1996). Thus, the urban-mobility community would do well to
understand the potential communities of users and possible market-place feedbacks that
may shape the course of adoption.

People’s transportation needs are clearly being shaped by the convergence of
computer and communications technologies. A feature article in the *Economist*
magazine (April 10, 2008) framed the future in terms of “new nomads” and the disappearance of
the “need- to- be- there”. The new nomadism is enabled through new technologies in
communications, but the social impact is the way these communications have shaped
interactions among people. The new nomadism changes buildings, cities, and traffic
because people are less tied to place. Formerly two places: home and work are now three:
home, work, and public, and occupancy of any one place is transient and malleable. As a
result, daily peaks in traffic volume are flattening and stretching out through the day.
There is less targeted point-to-point travel and more “foraging” for things and
experiences. The innovative opportunities for these new nomads will need to “travel with
them”.

As the urban-mobility communities seek to harness their collective brain-power, it
needs a virtual or real place for sustaining *innovators* (people), their activities—
innovating (verb), and their output--*innovations* (things). There needs to be a balance
between closed and open communities, as taught by the history of Silicon Valley, but
with a guiding principle that innovation can be fostered, not mandated, and that an
innovation community looks more like an artists colony than an office park.

**REFERENCES**


*The Economist* (April 10, 2008.)


New Mobility: The Next Generation of Sustainable Urban Transportation
Susan Zielinski
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We are on the verge of a transformation in urban transportation called New Mobility.

In a classic 1950s photograph, a scientific looking man in a light suit is dwarfed by a mammoth mainframe computer he’s programming. It is unlikely that the idea of a “nanopod” would have entered his mind, let alone mesh networking, GIS, or “Googling.” He wouldn’t have conceived of the connectivity that a mere half-century later has brought these elements together, transformed the world, and evolved into one of the fastest growing, most pervasive global industries.

Today, we are on the cusp of a comparable transformation for cities called New Mobility. Accelerated by the emergence of new fuel and vehicle technologies; new information technologies; flexible and differentiated transportation modes, services, and products; innovative land use and urban design; and new business models, collaborative partnerships are being initiated in a variety of ways to address the growing challenges of urban transportation and to provide a basis for a vital New Mobility industry (MTE and ICF, 2002).

Connectivity
An early and very successful example of integrated innovation in New Mobility is the Hong Kong Octopus system, which links multiple transit services, ferries, parking, service stations, access control, and retail outlets and rewards via an affordable, contactless, stored-value smart card. The entire system is designed and engineered to support seamless, sustainable door-to-door trips (Octopus, 2006).

A more recent innovation, referred to as New Mobility hub networks, began in Bremen, Germany, and is evolving and spreading to a number of other European cities, as well as to Toronto, Canada (Figure 1). New Mobility hubs connect a variety of sustainable modes of transportation and services through a network of physical locations or “mobile points” throughout a city or region, physically and electronically linking the elements necessary for a seamless, integrated, sustainable door-to-door urban trip (MTE, 2004). Hubs are practical for cities in the developed or developing world because they can be customized to fit local needs, resources, and aspirations. Hubs can link and support a variety of diverse elements:
Factors Driving the Development of New Mobility
The evolution of New Mobility is inspired by emerging innovations and propelled by pressing needs, not the least of which is rapid urbanization. Although a few cities are shrinking, especially in the developed world, by 2030 more than 60 percent of the world population and more than 80 percent of the North American population will live in urban regions (UN, 1996). With increasing motorization, traffic volume and congestion are already resulting in lost productivity and competitiveness, as well as health and other costs related to smog, poor air quality, traffic accidents, noise, and, more recently, climate change (WBCSD, 2001).

At the same time, sprawling, car-based, urban-development patterns can mean either isolation or chauffeur dependence for rapidly aging populations, as well as for children, youths, and the disabled (AARP, 2005; Hillman and Adams, 1995; O’Brien, 2001; WBCSD, 2001). In developing nations, aspirations toward progress and status often translate into car ownership, even as the risks and costs of securing the energy to fuel these aspirations rise (Gakenheimer, 1999; Sperling and Clausen, 2002; WBCSD, 2001).

Engineering for New Mobility
The factors described above have created not only compelling challenges for engineering, but also opportunities for social and business innovation. New Mobility solution building is supported by new ways of thinking about sustainable urban transportation, as well as emerging tools and approaches for understanding, implementation, and commercialization. In this article, I focus on three frontiers of thinking and practice for New Mobility: complexity; accessibility; and new business models.

Complexity
Tools for Understanding
A variety of tools and approaches have been developed to support the analysis and modeling of complex urban transportation systems. At least three types of complementary systems analysis (top-down, bottom-up, and simulations) can be applied to transportation and accessibility. Top-down analyses generally start with self-generated variables or hypotheses and develop a causal-loop diagram using software that highlights patterns, dynamics, and possible intervention points. Once a basic analysis is
complete, more in-depth data gathering and modeling can be done. Some of the most extensive transportation-related work of this kind has been undertaken by Professor Joseph Sussman at M.I.T. (Dodder et al., 2002; Sussman, 2002; Sussman and Hall, 2004). Figure 2 shows a passenger-transportation subsystem for Mexico City.

Bottom-up, or agent-based, models, are computer-based models that use empirical and theoretical data to represent interactions among a range of components, environments, and processes in a system, revealing their influence on the overall behavior of the system (Axelrod and Cohen, 2000; Miller and Roorda, 2006; Miller and Salvini, 2005; Zellner et al., 2003). Ethnographic research can also be applied to transportation as a bottom-up research tool. By giving subjects documentation tools (e.g., cameras) over a fixed period of time, patterns of behavior can be observed without interference by researchers. Simulations and scenario-building software can draw from and build upon both top-down and bottom-up analyses. Simulations graphically depict and manipulate transportation and other urban dynamics to inform decision making and identify opportunities for innovation. MetroQuest (2006) is a good example of an effective urban-transportation simulation tool.

**Sophisticated Solution Building**

Complex transportation challenges call for sophisticated solutions. “Single-fix” approaches (e.g., alternative fuels alone, pricing mechanisms alone, or policy changes alone) cannot address the serious urban challenges and conditions noted above. Informed by complex systems analysis, systems-based solution building involves “connecting the dots,” that is, enhancing or transforming existing conditions with customized, integrated innovations in products, services, technologies, financing, social conditions, marketing, and policies and regulations (ECMT, 2006; MTED and ICF, 2002; Newman and Kenworthy, 1999). Sophisticated solution building usually involves multisector interdisciplinary collaboration. A good example of systems-based solution building is the New Mobility hub network described above. Hub networks can catalyze engineering and business opportunities related not only to the design and implementation of individual product and service innovations, but also to the engineering of physical and digital connections between them.

**Accessibility**

Over the past 50 years, measures of regional and economic success have become increasingly linked to (motorized) mobility and speed of travel (TTI, 2005). This association originated in the West and has been widely adopted in cities of the developing world. However, transportation is only a means to an end, or a derived demand, so measures and applications of accessibility do not focus on how fast or how far one can travel in a certain period of time. Instead, they focus on how much can be accomplished in a given time frame and budget or how well needs can be met with available resources. For example, on a typical day in Los Angeles, you may drive long distances at high speeds to fit in three meetings. In Bremen, Germany, a more accessible place, you may be able to fit in five meetings and a leisurely lunch, covering only half the distance at half the speed and for half the price (Levine and Garb, 2002; Thomson, 1977; Zielinski, 1995).
Accessibility can be achieved in at least three ways: wise land use and design; telecommunication technologies that reduce the need for travel; and seamless multi-modal transportation. Among other benefits, connected accessibility options can help address the demographic, equity, and affordability needs of seniors, children, the poor, and the disabled. At the same time, integrated accessibility can help build more adaptable and resilient networks to meet the challenges of climate change and emergency situations in cities. Dynamic and flexible accessibility and communications systems can support quick responses to unforeseen urban events.

The University of Michigan’s SMART/CARSS project (2006) is currently developing an accessibility index to compare and rate accessibility in metropolitan regions, as a basis for urban policy reform and innovation (see sidebar).

New Business Models
In a 2002 study by Moving the Economy, the current value and future potential of New Mobility markets were measured in billions of dollars (MTE and ICF 2002). New Mobility innovations and opportunities go beyond the sectoral bounds of the traditional transportation industry. They encompass aspects of telecommunication; wireless technologies; geomatics; e-business and new media; tourism and retail; the movement of goods; supply chain management (Zielinski and Miller, 2004); the design of products, services, and technologies; real estate development; financial services; and more.

New Mobility innovations not only improve local competitiveness and quality of life (Litman and Laube, 2002; Newman and Kenworthy, 1999), they also provide promising export and economic development opportunities for both mature and “base-of-the-pyramid” markets (Hart, 2005; Prahalad, 2004). Because urban transportation represents an increasingly urgent challenge worldwide, and because urban mobility and accessibility solutions can, in most cases, be adapted and transferred, regions, nations, and enterprises that support New Mobility (supply-side) innovation, as well as industry clustering and the development of new business models, stand to gain significantly from transportation export markets in the coming years (MTE and ICF, 2002).

Engineering and Beyond
New Mobility has the potential to revitalize cities and economies worldwide and can open up a wealth of engineering and business opportunities. But obstacles will have to be overcome, not all of them related to engineering. For example, increased motorization and the high social status it represents in developing countries, along with seemingly unstoppable urban sprawl in the West, are challenges that must be addressed on psychological and cultural levels, as well as infrastructural and economic levels. Progress toward a positive, integrated, and sustainable future for urban transportation will require more than moving people and goods. It will also involve the complex task of moving hearts and minds.

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References


Bibliography


SIDEBAR

SMART (Sustainable Mobility and Accessibility Research and Transformation), an interdisciplinary initiative at the University of Michigan in Ann Arbor, is grounded in complexity theory and practice. The goal of the project is to move beyond purely technical and mobility-based approaches to urban transportation to address challenges and opportunities raised by the complex interactions of social, economic, environmental, and policy factors. A project of CARRS (Center for Advancing Research and Solutions for Society), SMART brings together experts on issues, theoretical approaches, and practical and policy applications to tackle the complexity, sophistication, impacts, and opportunities related to urban transportation and accessibility, particularly for growing urban populations worldwide. SMART works collaboratively across disciplines and sectors to:

- catalyze systemic and fundamental transformations of urban mobility/accessibility systems that are consistent with a sustainable human future
- harness emerging science on complex adaptive systems to meet future mobility and accessibility needs in an ecologically and socially sustainable way and identify “tipping points” to guide the evolution of such systems
- inform and develop integrated New Mobility innovation and business models
- provide diverse academic opportunities related to sustainable urban mobility and accessibility
- contribute to a growing multidisciplinary, multistakeholder, global network of applied learning in sustainable mobility and accessibility

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