A Review of System Dynamics Applications in Sustainable Urban Transportation

Irfan Batur, Qatar Foundation - Hamad Bin Khalifa University, Qatar
Muammer Koç, Qatar Foundation - Hamad Bin Khalifa University, Qatar

The European Conference on Sustainability, Energy & the Environment 2017
Official Conference Proceedings

Abstract
Towards the end of 20th century, ever-increasing pressures for the need of sustainable development have re-shaped our way of thinking in which sustainability is now widely accepted as a top priority. Most of the economic and social activities are provided via transportation. Thus, it is of great importance to achieve sustainable transportation for sustainable development, especially from the point of energy and carbon dioxide emission reduction. However, transportation systems are complex and involve social, economic and environmental aspects which call for employing a holistic approach rather than conventional methods. System dynamics (SD) is such a holistic methodology for studying and managing complex systems in order to make integrated assessments and policy decisions. While its conception and early applications have been mainly related to industrial applications (frequently referred to “industrial dynamics”), it has also been used recently for the analysis of transportation systems. The aim of this study is to explore the feasibility of SD for transportation-related energy consumption, CO2 emissions, health impacts and economics by conducting a critical literature review of SD applications in the urban transportation field. Through the end of paper, implications and results of the review are shared as conclusion in addition to further research areas in the field.

Introduction

Our current road-based transportation system which is mainly dependent on automobile use causes a wide range of formidable problems. These include traffic congestion, air pollution, noise, accidents and related fatalities, depletion of non-renewable resources and inaccessibility of amenities and services. To illustrate this, more than one-quarter of total U.S. greenhouse gas emissions come from the transportation sector and light vehicles are responsible for 59% of transportation energy use (C2ES, 2012). Due to the accidents on roads, approximately one million people dies apart from millions of injuries (WHO, 2010). These are just a few examples to illustrate detrimental effects of transportation on sustainable development especially due to automobile use. Therefore, the current transportation system especially in urban areas may be considered as unsustainable from various viewpoints. Furthermore, transport demand, however, increases as economic growth increases (European Comission, 2012) which will make the situation even worse in the years to come. To counter this challenge of moving towards sustainable transportation, much more effort is needed. To direct investments and efforts into the right places and achieve livable and sustainable urban areas, understanding dynamics of transportation and making projections under different scenarios for upcoming years is of vital importance (Birol, 2014).

System dynamics (SD), originally called industrial dynamics, was developed by Jay Forrester from MIT in the late 1950s (Forrester, 1958). It is a methodology for studying and managing complex feedback systems to make integrated assessments and policy decisions (Saeed, 1994). Since many systems such as structure of a corporation, an urban area, or economic processes are complex, making it difficult to understand and control. In this sense, SD seeks, firstly, to identify the underlying structure of a system to gain insight into patterns of how a system behaves, then to focus on interactions of the system's components into each other to understand the roles each component plays rather than concentrating on specific events, and lastly, to try contributing designing process of policies which seek to eliminate unwanted patterns of behavior through modifying the underlying structure of a system (Kirkwood, 1998). Although its early applications were mainly limited to industrial management, it has been applied to various fields by time, including government policy (Forrester, Mass, & Ryan, 1976), healthcare (Homer & Hirsch, 2006; Lane, Monefeldt, & Rosenhead, 2000; Royston & Dost, 1999), the automobile industry (Hayter, 1997; Kumar & Yamaoka, 2007), electrical power industry (Ford, 1997), urban studies (Duran-Encalada & Paucar-Caceres, 2009; Dyson & Chang, 2005; Forrester, 1970; Han, Hayashi, Cao, & Imura, 2009). Furthermore, Abbas and Bell (1994) showed that it is also applicable to transportation field due to various advantages in transportation field in comparison with traditional transport modeling.

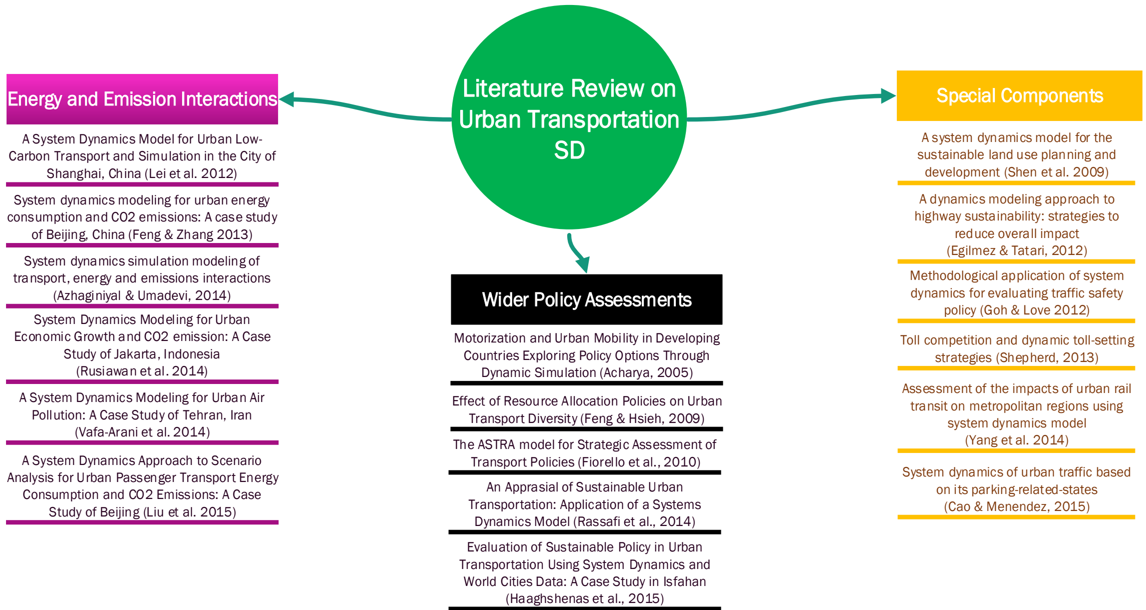

Figure 1: Selected SD articles on the components of urban transportation within the scope of this paper

After Abbas and Bell (1994) particularly suggested SD as a well-suited approached to strategic policy analysis and as a support tool for decision making processes, noteworthy applications of SD into transportation field have since evolved. Thus, we have identified SD as an appropriate approach to investigate and study transportation status and its future expectations in urban areas. Our review focuses on the applicability of SD in the field of sustainable urban transportation and indicates that SD is applied in numerous components of sustainable urban transportation including wider-policy assessments studies, studies focusing on interaction between transportation, emissions and energy consumption, and studies focusing on special components of urban transportation (see Figure 1).

Wider-policy assessments studies

Transportation in urban areas manifests a multidimensional problem in which one may approach them from different angles on a small scale with few dimensions or on a large scale with many dimensions. In this direction, various different policies and interventions have been developed over time. Acharya (2005) proposed an SD model in particular for developing countries to experiment three scenario options including road investment, early rapid transit investment, and late rapid transit investment against business as usual scenario. The model tests the effects of these options on congestion, modal share and attractiveness of public transportation, motorization and urban sprawl. Simulation results revealed that introduction of off-road rapid transit is important not only to improve modal share and attractiveness of public transport but also to mitigate traffic congestion. However, it is also revealed that too late development of rapid transit may bring about limited impact.

In a similar fashion to Acharya's study (2005), Feng and Hsieh (2009) proposes a hybrid model integrating SD, cognitive maps and a sensitivity model to tackle problems related to transportation investment. In particular, they try to answer the questions when to invest and how to allocate resources over time. Taipei case is used to empirically illustrate the approach to enhance the managerial implications in the city. The study reveals that an increase in private vehicle trips reduces transport diversity which causes an increase in emissions, energy consumption, and accidents. Therefore, policies which control the growth of car use are the most effective for meeting the needs of stakeholders. However, the system is shown to be insensitive to tuning policy implementation delays due to managerial choices of resource allocation.

In parallel with above studies, Fiorello et al. (2010) demonstrates an overview of the ASTRA model which have been developed to investigate strategic policy scenarios at the European level. These include scenarios concerning energy scarcity, high oil prices, and technological investments in the transport sector and application of these measures included in the European transport policy. This model links transport demand, economy, vehicle fleet and environmental effects. Thus, it enables integration of multidimensional assessment of alternative scenarios. Additionally, the authors provide advantages of using ASTRA for transport modeling and illustrate their points by providing an example project's results (iTREN-2030 European project).

With the increase in concern over sustainable development, two different studies were published which take interaction one step further to include all of the three pillars of sustainability. Rassafi et al. (2014) proposes a new comprehensive model to evaluate sustainable urban transportation. The model includes economic, environmental, social, and urban transportation variables. They validated the model by using actual data for years 1994 to 2009 of Masshad, Iran. Then, a simulation model was run from 2009 to 2044. Effects of two policies "Increasing average car occupancy", and "increasing salvage rate of vehicles" were analyzed. It is revealed that increasing salvage rate of vehicles had superior effects on minimizing the annual fuel consumption in Masshad. As a result, the authors claimed that the proposed approach has the capability to find the optimal strategy for sustainable urban transportation. Haghshenas et al. (2015) developed an SD model on world cities data to analyze sustainable transportation dynamics for Isfahan, Iran, to evaluate different transportation development scenarios. Trip generation, modal share, transportation supply and equilibrium between supply and demand are taken as key modules of SD model. Nine different indicators were selected and assigned into environmental, economic and social key categories which are considered as key outputs of the model. For Isfahan, the model results revealed that urban transportation policymakers should develop policies pertinent to non-motorized transit network development after monitoring future scenarios. The authors also claim that the model could be applied to other cities as well in policy development and evaluation to identify the best sustainable policies.

Studies related to interaction between transportation, emissions and energy consumption

Currently transportation systems mainly run on fossil fuels. This is important from two aspects: (1) it increases pressure on non-renewable energy resources and (2) causes air pollution more importantly CO_2 emissions which result in various problems including climate change. To this end, Azhaginiyal and Umadevi (2014) focus on the interaction between transport, energy and emissions. They developed a new SD model to analyze the existing transport supply and demand in Chennai, India by using data inventory on energy requirement and emissions from transport sector to determine the energy requirement and emissions caused from transport sector in the year 2026. Results of the study reveal that personalized modes contributes to about 80% of trips and about 300% increase in fuel demand for 'business as usual scenario'. However, results indicate that the scenario of augmenting public transport and simultaneously restricting growth of personalized vehicles showed a substantial decrease in energy consumption (nearly 65%) and nearly 50% reduction in emissions from personalized travel modes. Similarly, Lei et al. (2012) studied dynamic relationship between society, economy, motor vehicles, transport infrastructure, city traffic management level and urban transportation carbon emissions through building an urban low-carbon transport system. For the case of Shanghai, China, the results indicate that rapid increase of private cars is an important driving factor of carbon emission and thus strengthening urban transport demand management and improving urban transport structure is essential for building urban low-carbon transport.

From a wider perspective, Vafa-Arani et al. (2014) propose a model in order to estimate behavior parameters affecting air pollution in Tehran, Iran, by taking into account urban transportation and air polluting industries. They run the proposed model under several scenarios for testing various policies including road construction, technology improvement in fuel and automotive industries, traffic control plans, and development of public transportation. As a result, the study indicates that technological improvement in the fuel and automotive industries and development of public transportation infrastructures are more effective policies in order to mitigate air pollution. Likewise, Feng et al. (2013) developed an SD model in order to capture energy consumption and CO_2 emissions trends for Beijing over the years 2005-2030. According to the results, it is expected that the service sector will gradually replace the industrial dominant status in energy consumption as the largest energy consuming sector, followed by industrial and transport sector.

Rusiawan et al. (2015) studied relations between CO_2 emission and economic growth in Jakarta, Indonesia, from SD perspective. They tested three different scenarios (namely, business as usual, development of green open space, and increasing share of renewable energy) during the period of 2009-2029 by taking into account economic growth and its effects on population, transportation, energy consumption etc. As a result, they propose a role model of sustainable urban development policy for Jakarta.

More recently, Liu et al. (2015) built a new SD model for Beijing urban passenger transport carbon model which includes economy, population, transport, energy consumption, and CO_2 emission subsystems for testing a variety of policy options. These individual policies are the technical progress (TP), priority to the development of public transport (PDPT), travel demand management (TDM), administrative rules and regulations management (ARM). According to the results, the optimal implementation sequence of each individual policy is provided. However, it is also indicated that the effect of comprehensive policy (CP) which is a policy scenario integrating all of PDPT, TDM, TP, and ARM scenarios was better than any of the individual policies pursued separately.

Studies related to special components of urban transportation

Elements of mobility and access management for urban transportation are nicely summarized by Meyer (1997) (see Figure 2). There are various studies which particularly focus on these specifics elements. Shen et al. (2009) focused on sustainable land use and urban development in Hong Kong and found that compact high-density scenarios in terms of land use are more sustainable with investment in rail based transport over car infrastructure. Egilmez and Tatari (2012) aimed to reduce CO_2 emission associated to US highway system sustainability problem to meet the Liberman and Warnet Climate Act's targets by 2050. They tested three potential strategies (fuel efficiency, public transportation, and electric vehicle usage) for policy making and indicate via their results that hybrid implementation of individual policies is crucial on the success of policy making. In similar fashion, Yang et al. (2014) analyze impacts of urban rail transit system on metropolitan regions from the aspects of urban traffic, economy, society and environment by building an SD model. They carried out a case study of Guangzhou, China to verify their model. As a result, they claim that their SD is a feasible and effective approach for simulating complex traffic system and government decision-making processes.

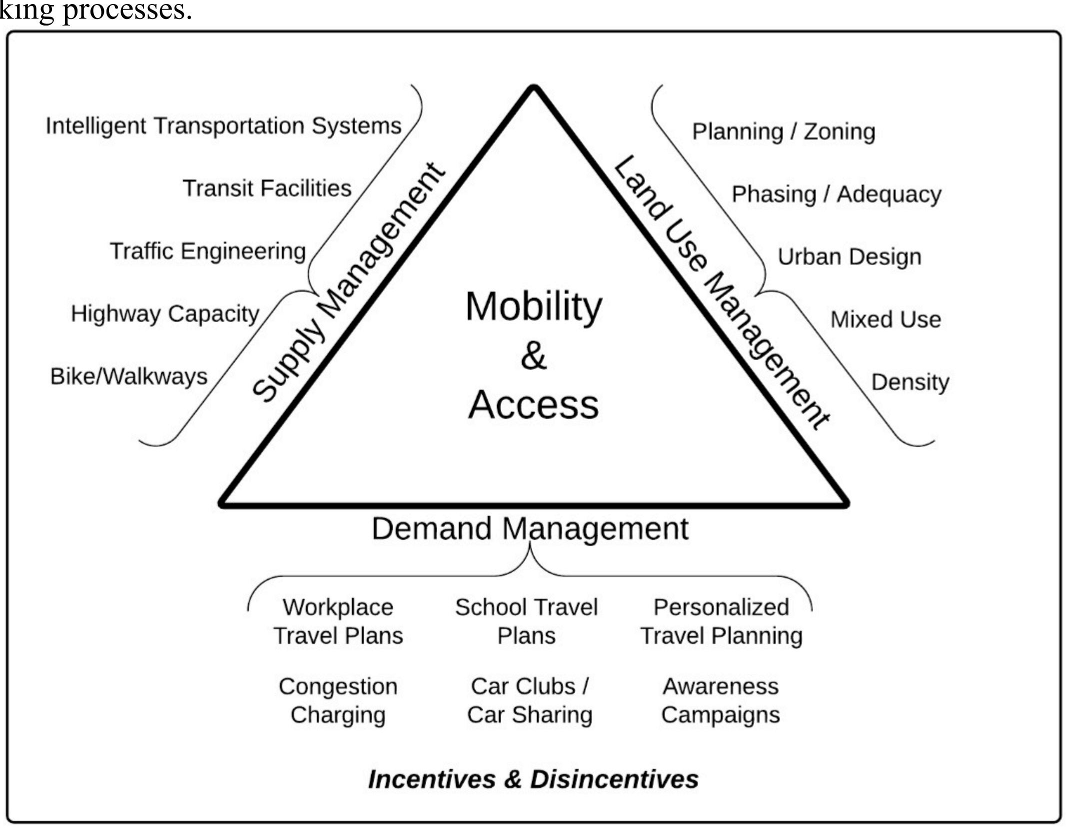

Figure 2: Elements of Mobility and Access Management (reproduced from (Meyer, 1997)*)*

In more detail, Goh and Love (2012) propose two models to demonstrate how SD approach can facilitate and encourage macro and meso level analysis of traffic safety policy and suggested that SD is the most appropriate for formulating macro level policy. Cao and Menendez (2015) propose a model which shows dynamics of urban traffic based on its parking related states and can be used efficiently to evaluate urban traffic and parking systems macroscopically. Overall, they conclude that their proposed model is useful to study multiple strategies and scenarios for traffic operations and control, transportation planning, land use planning, or parking management. Shephered (2013) used SD approach to model both user's route choice and demand response to changes in generalized cost and model the toll operators' decision rules or toll-update strategies. The results indicate that solutions depend upon the frequency of decisions or changes in toll level, and errors are related to the disequilibrium which are present as users respond to changes in toll levels.

Conclusion

To conclude, SD has been using diversely in transportation field to evaluate different policy options, address possible intervention policies and help decision makers. It has been implemented to make wider policy assessments such as investments strategies aiming when to and how to invest. Besides that, it has been used to determine dynamic relationship between transport, emissions and energy consumption in urban areas. More specifically, there are studies which employ SD for modeling special components of urban transportation such as highway sustainability, and traffic safety. In particular, each study uses one urban area to test their developed SD models in order to provide its efficient use.

Some recent studies imply the way for further research areas. Shepherd (2013) addresses the gap for lacking comparison studies between cities. Feng (2013) indicates the importance of different sensitivity analysis at the micro levels to make results more robust and reliable. Liu et al. (2015) reveals their studies' further direction into that universally use of their developed model needs to be further studied to take into account of each city's own characteristics and development stage. In relation to these, Egilmez and Tatari (2012) addresses sustainability footprint generation and involvement of society's sustainability awareness to be considered as future work. Besides that, there isn't one particular study available which focuses on cities from resource-rich counties based on our review. Therefore, the next research questions in this fields have to address urban transportation policies based on comparisons of different cities in terms of energy consumption, CO_2 emissions, economy and society. The cities should be selected in the way of differentiating resource-rich countries and resource-poor countries, developed cities and developing cities, and cities with all sizes. This includes taking into consideration of cities own characteristics, sustainability metrics and different sensitivity analysis.

References

Abbas, K., & Bell, M. (1994). System dynamics applicability to transportation modeling. *Transportation Research Part A: Policy and Practice*. Retrieved from http://www.sciencedirect.com/science/article/pii/0965856494900221

Acharya, S. R. (2005). Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 4113 - 4128, 2005, *6*, 4113–4128.

Azhaginiyal, A., & Umadevi, G. (2014). System Dynamics Simulation Modeling of Transport, Energy and Emissions Interactions. *Civil Engineering and Architecture*, *2*(4), 149–165. https://doi.org/10.13189/cea.2014.020401

Birol, F. (2014). *World Energy Investment Outlook*. Paris. Retrieved from https://www.iea.org/publications/freepublications/publication/WEIO2014.pdf

C2ES. (2012). Transportation Overview | Center for Climate and Energy Solutions. Retrieved November 9, 2015, from http://www.c2es.org/energy/use/transportation

Cao, J., & Menendez, M. (2015). System dynamics of urban traffic based on its parking-related-states. *Transportation Research Part B: Methodological*, *81*, 718–736. https://doi.org/10.1016/j.trb.2015.07.018

Duran-Encalada, J., & Paucar-Caceres, A. (2009). System dynamics urban sustainability model for Puerto Aura in Puebla, Mexico. *Systemic Practice and Action …*. Retrieved from http://link.springer.com/article/10.1007/s11213-008-9114-8

Dyson, B., & Chang, N. (2005). Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling. *Waste Management*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0956053X04001850

Egilmez, G., & Tatari, O. (2012). A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact. *Transportation Research Part A: Policy and Practice*, *46*(7), 1086–1096. https://doi.org/10.1016/j.tra.2012.04.011

European Comission. (2012). EU Transport in figures. Statistical pocket book 2012. Retrieved from http://ec.europa.eu/transport/facts-fundings/statistics/doc/2012/pocketbook2012.pdf

Feng, C.-M., & Hsieh, C.-H. (2009). Effect of Resource Allocation Policies on Urban Transport Diversity. *Computer-Aided Civil and Infrastructure Engineering*, *24*(7), 525–533. https://doi.org/10.1111/j.1467-8667.2009.00608.x

Feng, Y. Y., Chen, S. Q., & Zhang, L. X. (2013). System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. *Ecological Modelling*, *252*, 44–52. https://doi.org/10.1016/j.ecolmodel.2012.09.008

Fiorello, D., Fermi, F., & Bielanska, D. (2010). The ASTRA model for strategic assessment of transport policies. *System Dynamics Review*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/sdr.452/abstract

Ford, A. (1997). System dynamics and the electric power industry. *System Dynamics Review*. Retrieved from http://xmile.systemdynamics.org/wp/wp-content/userup/Ford-1997-System-Dynamics-and-the-Electric-Power-Industry.pdf

Forrester, J. (1958). Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review*. Retrieved from https://scholar.google.com/scholar?hl=en&q=forrester+industrial+dynamics&btnG=&as_sdt=1%2C5&as_sdtp=#1

Forrester, J. (1970). Urban dynamics. *IMR; Industrial Management Review (Pre-1986)*. Retrieved from http://search.proquest.com/openview/111accf0f58d4e948aa8aa8e8e44530a/1?pq-origsite=gscholar

Forrester, J., Mass, N., & Ryan, C. (1976). The system dynamics national model: understanding socio-economic behavior and policy alternatives. *Technological Forecasting and Social …*. Retrieved from http://www.sciencedirect.com/science/article/pii/0040162576900445

Goh, Y. M., & Love, P. E. D. (2012). Methodological application of system dynamics for evaluating traffic safety policy. *Safety Science*, *50*(7), 1594–1605. https://doi.org/10.1016/j.ssci.2012.03.002

Haghshenas, H., Vaziri, M., & Gholamialam, A. (2015). Evaluation of sustainable policy in urban transportation using system dynamics and world cities data: A case study in Isfahan. *Cities*, *45*, 104–115. https://doi.org/10.1016/j.cities.2014.11.003

Han, J., Hayashi, Y., Cao, X., & Imura, H. (2009). Application of an integrated system dynamics and cellular automata model for urban growth assessment: A case study of Shanghai, China. *Landscape and Urban Planning*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204608002351

Hayter, R. (1997). *The dynamics of industrial location: the factory, the firm, and the production system*. Retrieved from http://faculty.washington.edu/krumme/450/hayter.html

Homer, J., & Hirsch, G. (2006). System dynamics modeling for public health: background and opportunities. *American Journal of Public Health*. Retrieved from http://ajph.aphapublications.org/doi/abs/10.2105/AJPH.2005.062059

Kirkwood, C. (1998). System Dynamics Methods. *College of Business Arizona State University USA*. Retrieved from http://down.cenet.org.cn/upfile/33/2005814153535124.pdf

Kumar, S., & Yamaoka, T. (2007). System dynamics study of the Japanese automotive industry closed loop supply chain. *Journal of Manufacturing Technology …*. Retrieved from http://www.emeraldinsight.com/doi/abs/10.1108/17410380710722854

Lane, D., Monefeldt, C., & Rosenhead, J. (2000). Looking in the wrong place for healthcare improvements: A system dynamics study of an accident and emergency department. *Journal of the Operational Research …*. Retrieved from http://www.jstor.org/stable/254183

Lei, X., Zhang, J., & Li, J. (2012). A system dynamics model for urban low-carbon transport and simulation in the city of Shanghai, China. *AISS: Advances in Information Sciences and Service …*, *4*(January), 239–246. https://doi.org/10.4156/AISS.vol4.issue1.31

Liu, X., Ma, S., Tian, J., Jia, N., & Li, G. (2015). A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO2 emissions: A case study of Beijing. *Energy Policy*, *85*, 253–270. https://doi.org/10.1016/j.enpol.2015.06.007

Meyer, M. D. (1997). A Toolbox for Alleviating Congestion and Enhancing Mobility. Washington D.C.: Institue of Transportation Engineers.

Rassafi, A. A., Jafari, M. O., & Javanshir, H. (2014). An Appraisal of Sustainable Urban Transportation : Application of a System Dynamics Model, *2*(1).

Royston, G., & Dost, A. (1999). Using system dynamics to help develop and implement policies and programmes in health care in England. *System Dynamics …*. Retrieved from http://search.proquest.com/openview/3d20519075618430e9b013c8d2d11fa7/1?pq-origsite=gscholar

Rusiawan, W., Tjiptoherijanto, P., Suganda, E., & Darmajanti, L. (2015). System Dynamics Modeling for Urban Economic Growth and CO2 Emission: A Case Study of Jakarta, Indonesia. *Procedia Environmental Sciences*, *28*(SustaiN 2014), 330–340. https://doi.org/10.1016/j.proenv.2015.07.042

Saeed, K. (1994). Development planning and policy design: a system dynamics approach. Retrieved from https://scholar.google.com/scholar?q=system+dynamics+government+policy&btnG=&hl=en&as_sdt=0%2C5#0

Shen, Q., Chen, Q., Tang, B., Yeung, S., Hu, Y., & Cheung, G. (2009). A system dynamics model for the sustainable land use planning and development. *Habitat International*, *33*(1), 15–25. https://doi.org/10.1016/j.habitatint.2008.02.004

Shepherd, S. (2013). Toll Competition and Dynamic Toll-Setting Strategies. *International Journal of Sustainable Transportation*, *7*(February 2015), 186–203. https://doi.org/10.1080/15568318.2013.710122

Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., & Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. *Transportation Research Part D: Transport and Environment*, *31*, 21–36. https://doi.org/10.1016/j.trd.2014.05.016

WHO. (2010). Number of road traffic deaths. Retrieved November 9, 2015, from http://www.who.int/gho/road_safety/mortality/traffic_deaths_number/en/

Yang, Y., Zhang, P., & Ni, S. (2014). Assessment of the Impacts of Urban Rail Transit on Metropolitan Regions Using System Dynamics Model. *Transportation Research Procedia*, *4*, 521–534. https://doi.org/10.1016/j.trpro.2014.11.040