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Abstract

System dynamics (SD) is a method for learning about complex systems and it includes a range of tools such as causal loop diagrams and computer simulation. SD has been used to facilitate the analysis of complex physical and social systems, e.g. water resources, climate change and industrial accidents. One of the key reasons for its growing popularity is that SD allows policy “experimentation” and facilitates discussion of “what-if” scenarios. Due to the complexity of traffic policies, SD has been used to facilitate traffic policy analysis. However, there is a lack of application of SD in traffic safety policy, which tends to focus on micro level issues, e.g. interactions between the driver, infrastructure and the vehicle. Even though such micro level analysis are important, macro traffic safety policies can create more sustainable systems that pre-empt safety issues and reduce likelihood of traffic accidents. This paper presents two preliminary case studies of how SD can facilitate and encourage macro and meso levels traffic safety policy. In the first case study, a small SD model was created to assess the policy options to encourage purchase cars with higher safety rating. In the second case study, an existing SD simulation model that evaluates the impact of public transport policies on travel time is extended to include traffic safety consideration. The authors draw on the experience of developing the two hypothetical case studies to assess the usefulness and challenges of using SD to facilitate traffic safety policy.

1 Introduction

“Road traffic injuries are a worldwide disaster.” (Naci et al., 2009)

Traffic safety is a significant issue in most countries. According to the World Health Organization (WHO), an estimated 1.2 million people die from road accidents every year (Breen and Seay, 2004). In the same report, WHO also predicted that, by 2020, road injuries will be the third leading contributor to the global burden of disease and injury. Even though the projection of future traffic fatalities for high income countries is comparatively less acute than low income countries (Kopits and Cropper, 2005), the number of fatalities remain at an unacceptable level.

In response to the worldwide problem of road accidents, considerable amount of effort has been expended over the years to reduce the impact of road trauma. Morrison (2003) summarised numerous traffic safety interventions that have been utilised, for e.g. motorcycle helmets and seatbelts, raising minimum drinking age above 18 years, traffic-calming engineering measures, speed camera, public lighting, random breath testing, enforcement and graduated licensing. The decisions to implement these traffic safety
interventions are frequently based on impact assessments or cost-benefit analyses (CBA) of road transport initiatives. Even though traffic safety is an important issue, the impacts of safety initiatives have to be considered in a more holistic or systemic manner, taking into account other components and goals (e.g. mobility and environmental) of the road transport system. Similarly, other non-safety initiatives in the road transport system have to consider their implications on traffic safety so as to make publicly rational decisions (Cochran and Malone, 2005).

Publicly rational decisions for the road transport sector are hard to be determined due to the complexity of the road transport system. In its simplest form the road transport system can be described by its essential components: vehicles, drivers and the road infrastructure. However, this limited system exists within the larger social, business, government, and natural environmental contexts (Stoop and Thissen, 1997, Toleman and Rose, 2008). These elements include policies from different levels of governments, funding and pricing systems, legislated requirements, and many diverse expectations, amongst other things. The road transport system is essentially a large ‘open’ system with a lack of clear boundaries. All stakeholders of the road transport system can impact on the system simultaneously, but none has direct control of the entire system. Furthermore, the road transport system has a range of goals to satisfy and a rational decision is inherently difficult.

‘Dynamic complexity’ (Goh et al., 2010a, Senge, 2006, Sterman, 2000) is another form of complexity that prevails in a road transport system. Goh et al. (2010a) highlighted that dynamic complexity arises when actions and consequences are separated in time and causation of consequences involves ‘messy’ coupling of issues with indistinct root causes. Dynamic complexity has been gaining attention in occupational health and safety research (e.g. Cooke and Rohleder, 2006, Goh et al., 2010b, Marais et al., 2006, Rudolph and Repenning, 2002, Salge and Milling, 2006), but deserves more attention in traffic safety research. Stoop and Thissen (1997) highlighted the importance of understanding the complexity of transport systems through integrated assessment tools. However, Stoop and Thissen (1997) may be misinterpreted to imply the need to widen the scope of road transport policy analysis to include more variables into consideration. Even though widening the scope of analysis is essential at times, system dynamics emphasises the importance of understanding the systemic structure driving the pattern of events or outcomes, e.g. traffic safety consequences, is more critical (Senge, 2006, Sterman, 2000).

This paper assesses the use of system dynamics methodology (Sterman, 2000) in road safety policy analysis. Two preliminary case studies are presented and the experiences of the authors in developing these case studies are drawn upon to assess the strengths and weaknesses of system dynamics in road transport policy analysis.

2 Transport and Road Safety Policy Assessment

Most transport policy analysis approaches are based on assessment of proposed changes to an existing situation. CBA is arguably the most common method used to facilitate transport policy analysis (Haezendonck, 2007). CBA assesses the costs and benefits of different transport policies in monetary terms and provides quantitative assessment measures to support decision making. For instance, a CBA of a large-scale road project is based on the benefits which accrue when a change is made to the transport system (i.e. the road project is constructed) in comparison to the costs due to the change. To incorporate safety concerns, CBA typically incorporates a Value of Statistical Life (Wijnen et al., 2009) such that any forecast of accidents can be translated into monetary terms.
Transport CBA occurs at macro, meso and micro levels. A macro level analysis may describe the relationship between economic factors, such as gross domestic product (GDP) or population, deaths and injuries on roads. A meso level analysis could describe the consequences of a major road project, typically assessed according to economic analysis. A micro model could assess an individual location or policy intervention such as electronic stability control in vehicles. Models can be constructed in numerous ways, but for transport safety investigations they tend to be quantitative regressions of related variables (e.g. Gokdag et al., 2004, Ma and Kockelman, 2006), epidemiological studies (e.g. Marchetti et al., 2009, Naci et al., 2009) or before and after analyses (e.g. Passmore et al., 2010, Seethaler and Rose, 2009).

Arguably the current CBA approaches are static (Schade and Rothengatter, 2003) as they are usually based on relatively simple estimates of parameters. Numerous simplifying assumptions have to be made to deal with the non-linearity and complexity of the system. Schade and Rothengatter (2003) suggested the use of system dynamics modelling methods to allow ‘dynamic CBA’ to be conducted at the macro, meso and micro levels so as to improve the quality and accuracy of policy analysis. Despite the potential of system dynamics, there appears to be a lack of application of the method in transport and road safety analysis.

3 Overview of Systematic Dynamics

System dynamics (also known as systems thinking (Senge, 2006)) is essentially a method to model the real world (Bougon, 1992, Burchill and Fine, 1997, Forrester, 1961, Kim and Anderson, 1998, Lyneis, 1999, Senge, 2006, Sterman, 2000, Sutanto et al., 2008) to facilitate analysis, communication and learning. System dynamics, unlike traditional approaches that emphasize linear cause and effect, focuses on feedback between variables in a system. The focus on feedback enables a more holistic view of the real world and places emphasis on complex dynamics of real world systems. System dynamics models have been used to address an array of problems such as delay and dispute causation (Williams et al., 1995a, Williams et al., 1995b), litigation (Ackermann et al., 1997), error causation (Love et al., 2008, Love et al., 2009), the impact of change orders and rework (Cooper, 1980, Love et al., 2002), contract design (Saeed and Brook, 1996), and organizational accidents (Goh et al., 2010a, Goh et al., 2010b).

Some of the reported benefits of system dynamics are:

(1) enables dynamic and non-linear analysis (Schade and Rothengatter, 2003),
(2) helps to unravel dynamic complexity by surfacing the underlying structure of the system (Senge, 2006), and
(3) provides a platform for policy makers and stakeholders to interact with the model to visually understand the possible impacts of policies and strategies (Ben Maalla and Kunsch, 2008).

A system dynamics analysis typically involves the following steps (Sterman, 2000):

(1) Problem articulation
(2) Formulation of dynamic hypothesis
(3) Formulation of a simulation model
(4) Testing
(5) Policy design and evaluation

Problem articulation involves specifying the problem of concern and scoping the analysis to prevent including too much or too little detail in the model. At the problem articulation stage, 'reference modes' or time series charts of key parameters are used to explain the system behavior of concern. The formulation of dynamic hypothesis usually employs qualitative methods to create causal loop diagrams (e.g. Goh et al., 2010a, Goh et al., 2010b, Marais et
al., 2006), which are essentially influence diagrams that allow circular connections between variables. Causal loop diagrams seek to hypothesize the important system structure that explains the observed phenomenon or reference mode. It should be noted that some authors do not create causal loop diagrams, but formulate a simulation model based on the problem definition (e.g. Chen et al., 2009, Han et al., 2010). Formulation of simulation model is not uncommon in the transport sector, but transport models tend to be developed at micro level (e.g. Cortes et al., 2010), or meso level (e.g. Eliasson and Mattsson, 2001), and may not be useful for macro policy analysis. In contrast system dynamics simulation models are frequently used for macro level analysis and can also be applied at micro and meso levels. Two of the most famous examples of macro level system dynamics simulation models are the World models by Forrester (1973) and Meadows et al. (2005). During testing, the simulation models will be assessed for their ability to mimic actual trends observed in the real world. Other tests include extreme condition tests to ensure that the model is robust against extreme values in key variables and sensitivity analyses to determine the impact of uncertainties on model outputs. Once the model is deemed to be credible it can be used for policy analysis, where users can assess a range of policy options by modifying different variables in the model at different simulation time.

3.1 Current Applications of System Dynamics in Transport Sector

The uptake of system dynamics in the transport sector appears to be sporadic. The only large scale implementation of system dynamics in the transport sector known to the authors is the European research project on Assessment of Transport Strategies (ASTRA) (Transport Research Knowledge Centre, 2004). The ASTRA developed a comprehensive model of the transport system with a wide range of modules or sub-models, e.g. macro-economics, infrastructure, road vehicle, population, traffic safety and traffic noise. These modules come together to enable policy analysis of a wide range of transport issues including traffic safety. The ASTRA model has been successfully modified and applied in different macro policy analyses demonstrating the potential of system dynamics (Helfrich and Schade, 2008, Martino et al., 2009). Interestingly, the ASTRA model was not reported in peer-reviewed journals and seems to have limited impact outside Europe. This may suggest that the model is Europe-specific, but the authors believe that the model can be contextualised to suit other regions and countries.

There has also been recent interest in system dynamics modelling of the impact of transport policy on environmental emission of air pollutants (Chen et al., 2009, Han et al., 2010). The work by Chen et al. (2009) and Han et al. (2010) arose due to the identification of the complexity of the transport system and the need for a tool to facilitate policy experimentation. In comparison to the ASTRA model, their recent work to applied on specific cities with smaller populations. However, the model created by Chen et al. (2009) has some similarities to the ASTRA model (Transport Research Knowledge Centre, 2004), where macro variables like GDP and population are modelled more explicitly and in detail. In comparison the model in Han et al. (2010) is more specific and macro factors are modelled as exogenous. In this sense, Han et al. (2010) is essentially a model at meso level.

With the exception of the ASTRA model, the authors were not able to identify models designed for system dynamics analysis of traffic safety policy. To better assess the strengths and weaknesses of applying system dynamics in assessing traffic safety policy, the authors developed two preliminary case studies that are presented below.

4 Preliminary Case Studies

Even though the preliminary case studies are based on hypothetical scenarios, the basic structures of the models are potentially useful for real world traffic safety issues. The case
studies are presented as platforms for discussions on the feasibility of system dynamics in road transport policy analysis. Detailed discussions of the models and the equations used are beyond this paper.

4.1 Improving ANCAP rating of passenger vehicles

Figure 1 ANCAP rating system dynamics model

In this case study, it is assumed that the Western Australian government is trying to encourage the use of higher Australasian New Car Assessment Program (ANCAP) rating passenger cars. The advantage of higher proportion of higher ANCAP rating passenger cars is the lower likelihood and severity of accidents. The simplified scenario in the case study involves only three-star and five-star ratings cars. The specific policy goal is to achieve an average of four-star rating for all cars in the state by 2020. The model presented in Figure 1 is based on Sterman’s (2000, p.393) network effect model and was created using the system dynamics software, Powersim. Even though the case is hypothetical, some of the variables (e.g. price of cars and car population) are based on actual data obtained from the Australian Bureau of Statistics (2010). The authors assumed that two of the key influences are network
Network effect is due to the size of the current population of 3-star or 5-star cars. The larger the population of a category of car, the more attractive it is for a person to purchase a car of the category due to compatibility, lower cost of maintenance and societal norm. Price effect is relatively straightforward, where the lower the price the more attractive a category of car is. Other effects are modelled as exogenous and random. The key policy tools evaluated are taxation on 3-star cars and subsidy for 5-star cars.

The population (known as stock in system dynamics) of each category of passenger cars are represented by the large rectangles in each of the corresponding sector. In the simulation, each time step will increase or decrease the stock of cars based on the rate of purchase and discard (or scraping) of the cars as represented by the double lined flows into or out of the stock. The inflow rates (new cars) are in turn influenced by the network effect and price effect. These effects have impact on market shares and are influenced by attractiveness factors that are based on multiplication of exponential functions used by Sterman (2000, p.394). These functions can also be based on regression analysis which is common in transport studies (e.g. Cafiso et al., 2010).

The model can be validated by measuring the goodness-of-fit between the model outcome and actual data. When empirical data are not available, expert opinion can be sought to assess the validity of the model. Since system dynamics model frequently involve high uncertainty, sensitivity analysis of key parameters should be conducted. Figure 2 and Figure 3 are examples of univariate sensitivity analyses on the model. Both sensitivity analyses are based on 500 runs of the simulation model. The average star-rating is numerically sensitive to both parameters and the 90% confidence bounds of the two analyses are similar in width. However, variations in 'Threshold for network effect' will have a bigger impact on the policy goals because the average star rating actually decreases for some of the values within the 90% confidence bound (see Figure 2). Identifying important parameters through sensitivity analyses will enable researchers to focus data collection efforts to decrease uncertainty. In addition, influential parameters can be high impact levers that policy makers can utilise to achieve policy goals. The readers are referred to Clemson et al. (1995) and Ford (1990) for more details on sensitivity analysis.
Sensitivity analysis - variation of 'Average Star Rating' with normally distributed 'Sensitivity to size of car population' (10% std. dev.)

Figure 3 Sensitivity analysis for ‘Sensitivity to size of car population’

The model can be used to test a range of policies (Figure 4 and Figure 5). Figure 4 shows the user-friendly interface that can be created to help policy analyst to change the parameters to determine their impact on the model outcomes. In this preliminary case study (see Figure 5), the network effect in favour of 3-star cars is so strong that very high tax and subsidy (45% each) are required to encourage sales of 5-star passenger cars. This is not surprising as the initial population of 3-star cars is at 9 million, while 5-star cars are at 3 million. This indicates that it is important to reverse the network effect by encouraging earlier disposal or upgrading of 3-star rating cars through incentive schemes. These extended policy options can also be modelled for further experimentation.

Figure 4 Controls for policy experimentation
The cost and benefit of the different policies can be estimated based on the model to facilitate CBA (see Figure 6). As discussed earlier, the benefits of reduction in number of accidents and fatalities can be estimated based on the Value of Statistical Life and incorporated into the CBA.

### 4.2 Safety impact of removal of public transport subsidy

The second case study is meant to evaluate the safety impact of changes to the subsidy for public transport in a hypothetical region that is newly developed. The core model is created by anonymous authors based on Sterman’s (2000, pp. 177-190) causal loop model of traffic congestion. The initial intent of the model is to evaluate the impact of different levels of subsidies for public transport on traffic congestion. The core model was developed in seven modules and a traffic safety module (see Figure 7) was included in the core model to assess the impact of the different policy options on traffic safety. In this case study, it is assumed that the region is a new development and the government is considering the benefits of
providing subsidies for public transport. Besides the impact on travel time, the effect on number of crashes is also assessed.

Figure 7 Traffic safety module

The traffic safety module in Figure 7 is essentially a balancing loop that seeks to maintain the number of crashes below a tolerable number of crashes. In the module, the government will implement different traffic safety policies (enforcement, education and infrastructure improvement) in response to the six-monthly crash rate. The policy response is especially strong when the number of crashes exceeds the tolerable number of crashes. The policy response will influence the crash rate and hence the actual number of crashes. The number of crashes is also dependent on the traffic volume. The traffic safety module is linked to other modules through the impact of the number of crashes has on attractiveness of driving. The higher the number of crashes, the less desirable it is to drive. This serves as a natural balancing effect.

Figure 8 Effect of different levels of subsidy on public transport on number of crashes

Four possible levels of subsidy were experimented. The impact on the six-monthly moving average number of crashes is presented in Figure 8. As the traffic volume increases the
number of crashes increases in all the scenarios. However, when the traffic congestion starts to set in, the impact of the public transit subsidy can be observed. It is apparent that the bigger the subsidy, the greater the impact on the number of crashes. The small subsidy is ineffective and should not be considered.

The same model produces a wide range of data on travel time and demand for roads. In addition, a wide range of sensitivity analysis and policy experimentation can be conducted. These details were not presented to keep the paper focused and succinct.

5 Discussions

The first case study demonstrates how system dynamics models of traffic safety policy can be created to facilitate policy experimentation. In comparison to the second case study, the first case study was a much smaller model and was developed with a more specific policy goal in mind. The second case study adopted a similar approach as the ASTRA model (Transport Research Knowledge Centre, 2004), where a module for traffic safety was inserted to a comprehensive model that could be used to assess a wide range of transport issues. The following discussions draw on the authors’ experience in developing the case studies to evaluate the potential of system dynamics in traffic safety policy analysis.

5.1.1 Advantages of system dynamics

System dynamics is a potentially useful approach for assessment of traffic safety and transport policies. The key advantages are its ability to incorporate highly non-linear relationship and include a wide range of variables. The equations in the model can include a broad range of regression equations that are commonly used in the transport sector. However unlike traditional regression analysis, system dynamics can consider large number of relationships and take into account the interactions between variables. Another key advantage of system dynamics is its user friendly interface that allows policy makers to conduct experimentation and identify important leverage points. The simulations can also be used as gaming platforms (e.g. Bakken et al., 1992, Dyner et al., 2009) to allow stakeholders to understand how their decisions impact on the system and on other stakeholders. These learning games can be used to educate transport policy makers about the impact of transport policies on road safety and promote a more holistic view of the transport system.

5.1.2 Level of Analysis

System dynamics modelling appears to be more suitable for meso or macro level modelling. This is because the simulation approach is based on flow and not discrete objects. This means that system dynamics methods, by default, has low level of resolution and may not be especially useful in assessing micro level issues such as safety of traffic junction design and impact of traffic-calming controls at specific locations. Even though it is computationally possible to convert the flows into discrete counts, it may be more efficient to utilise traditional traffic safety simulation tools for micro level analysis.

5.1.3 Validity of model

System dynamics software (e.g. Powersim, Stella and Vensim) are relatively user friendly and traffic safety researchers should not have major difficulties in learning the tool. However, as in any modelling tool, the ease of modelling may facilitate development of poorly validated models. The importance of quality data, sensitivity analysis and detailed model testing is critical. Nevertheless, as highlighted by Box (1987), Sterman (2000) and several other academics in different fields, all models are wrong, the key is whether the model is useful in achieving its aim. Thus, even when quality data are not available, models can still be developed based on expert opinion to facilitate development of preliminary models. Such
models are especially useful when the scenarios are too complex for experts to assess directly or when it involves new projects and quality data are not available. System dynamics models can be developed with minimal hard data and the area has accumulated substantial literature on the use of qualitative and judgement data (e.g. Burchill and Fine, 1997, Forrester, 1973).

5.1.4 Size of model and blackbox effect

Large system dynamics model can appear complex to the layman and hence discourage the use of the models by end users or end users may just accept the output without challenging the assumptions in the model (‘blackbox effect’). For example the ASTRA model (Transport Research Knowledge Centre, 2004) probably involves hundreds of parameters (or even more than a thousand) and it may appear impossible for end users to understand the model. To overcome this possible weakness, the involvement of end users, who are usually the policy makers, must begin during the development of the model. The policy makers should be involved in the definition of parameters and equations. In this way the policy makers will have confidence in the model and will be able to understand the intricacies of the model.

However, it is noted that large models are harder to maintain. Even with modularisation and systematic documentation, large models may be prone to errors. Thus, it is important to understand the purpose of the model and include details only when necessary. This indicates the importance of a systematic approach to system dynamics modelling. As discussed earlier, having a well-defined problem and purpose includes scoping the boundary of the model and defining factors as exogenous. A systematic approach helps prevent a “model-the-real-world” mistake, where modellers try to create models that mimic the real world so much that the model becomes too large for its purpose.

6 Conclusions

The paper evaluates system dynamics as a possible approach to facilitate traffic safety policy analysis. System dynamics is known for its ability to unravel complexity and to assist policy experimentation. Traffic safety policy is a complex topic that is frequently neglected by policy makers that may not take a systemic view when assessing transport policies. Two preliminary case studies were created and the authors draw on the experience from the case studies to assess the potential of system dynamics in improving traffic safety policy analysis. The study showed that system dynamics is a potentially powerful tool that has already been implemented in Europe. However, several cautionary notes were provided to guide the use of the tool in transport and traffic safety policy analysis.

7 References


