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A review of system dynamics models applied in transportation

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Abstract

It is 20 years since Abbas and Bell (1994) evaluated the strengths and weaknesses of system dynamics as an approach for modelling in the transportation area. They listed 12 advantages of the approach and in particular suggested it was well suited to strategic issues and that it could provide a useful tool for supporting policy analysis and decision-making in the transport field. This paper sets out a review of over 50 peer-reviewed journal papers since 1994 categorising them by area of application and providing a summary of particular insights raised. The fields of application include the take-up of alternate fuel vehicles, supply chain management affecting transport, highway maintenance, strategic policy, airport infrastructure and airline business cycles and a set of emerging application areas. The paper concludes with recommendations for future application of the system dynamics approach.

1. Introduction

Abbas and Bell (1994) outlined the modelling approach used in system dynamics and listed 12 advantages of the approach compared to traditional transport modelling. In particular they suggested the approach would be well suited to strategic policy analysis and as a support tool for decision-making. In essence, transportation systems are complex, they often involve a number of different stakeholders or agents which results in feedbacks with different time lags between the responses of each type of user. System dynamics models offer a whole system approach to transport planning and with this different perspective the importance of these feedbacks and lagged responses can be demonstrated to policy makers. The system dynamics platforms also offer specialised tools[1], which aid in the calibration of models, optimisation of policies and improve ease of use through flight simulators which all contribute to the understanding of the whole underlying system.

System Dynamics was initially developed by Forrester from MIT in the 1950-60s, (Forester, 1958) and is a powerful methodology developed from system theory, information science, organisational theory, control theory, tactical decision-making, cybernetics and military games. It uses a standard causal loop approach to develop qualitative models of a system which may be used to develop dynamic hypotheses before a quantitative stock-flow model is developed. Early applications were in business management but over the past few decades it has been applied to other areas, including government policy, healthcare, the automobile industry and urban studies (Sterman, 2000). The application of causal loop diagrams (which set out the causal links between concepts) may be used to bring out the “mental models” (how people think a system works) of different stakeholders and therefore help remove any barriers to implementation of a given policy. System dynamics approaches are becoming increasingly used in a hierarchical manner which allows systems and policies to interact across space and time. The holistic approach is well suited to the transport problems we now face. Using different modelling approaches can also produce significantly different outcomes on the design of policies. System dynamics can bring in other modelling structures and help explore the real drivers of future demand as well as explain how to change user perception and behaviour. Models can be built with stakeholders’ input and then used in the form of games or flight simulators for policy learning.

The aim of this review is to set out which areas of transportation research have applied system dynamics since the paper by Abbas and Bell, and in doing so highlight whether the studies have made use of the qualitative causal loop approach, the quantitative stock-flow modelling approach and which insights were possible (if any) over and above a more traditional modelling approach. The approach taken was to review only peer-reviewed journal articles between 1995 and 2013. Whilst there are many conference papers applying system dynamics approaches to transport problems, the element of peer-review was used to check for quality. A limited number of key word search terms including, transport, transportation, system dynamics, modelling were used and after filtering out via reading the abstracts over 50 papers are included in the review. The papers are categorised by area of application in what follows while the first section sets out some basics of the system dynamics approach for those who are unfamiliar with it. The paper then concludes with a discussion about future application areas.

2. Some basics of system dynamics

The system dynamics approach links qualitative and quantitative models. The qualitative models are best built with the input of the relevant stakeholders and are generally communicated with causal loop diagrams (CLD). The development of a CLD is part of the model building process and connects entities by causal relationships and as the diagram develops then feedback loops become evident. These loops are either positive (self-reinforcing) or negative (self-correcting or balancing) feedback loops. Reinforcing loops amplify what is happening in the system, i.e. where an increase in one

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[1] Rather than detail the various software platforms available the International system dynamics society provides a list of key products at the following link : **http://tools.systemdynamics.org/core-sd-software/**

parameter leads to an increase in another, and without a balancing loop then this leads to exponential growth. Balancing loops are relationships that oppose change, so in such a loop an increase in one entity leads to a decrease in another. When systems contain balancing and reinforcing loops then a dynamic equilibrium may be reached.

A basic example of a simple reinforcing and balancing loop in a system is shown in

1, adapted from Sterman, (2000). The causal loops represent the interaction between eggs, chickens and road crossings. The ‘eggs and chickens’ loop is reinforcing (denoted R) as more eggs lead to more chickens, which in turn lead to more eggs. If this loop was operating on its own, both chickens and eggs would increase exponentially. On the other hand, the ‘chickens and road crossings’ loop is balancing (denoted B); while an increase in chickens leads to an increase in road crossings, the increase in road crossings leads to fewer chickens due to them being run over (denoted by “-“). If this loop were operating alone, the chickens (and road crossings) would gradually decline to zero. As both loops interact, the path of eggs, chickens and road-crossings over time are dependent on the relative rates but will eventually reach a dynamic equilibrium. Important elements of the diagram are the linking arrows with polarity + or – assigned to show causal links. A positive sign is used to show that an increase in the first entity causes an increase in the second entity (all else held constant). More chickens means more eggs and more road crossings. A negative sign is used to show that an increase in the first entity causes a reduction in the second. More road crossings means less chickens. With more complex loops, a positive feedback loop is one where there are an even number of negative links (or none); and a negative feedback loop is one where there are an odd number of negative links.

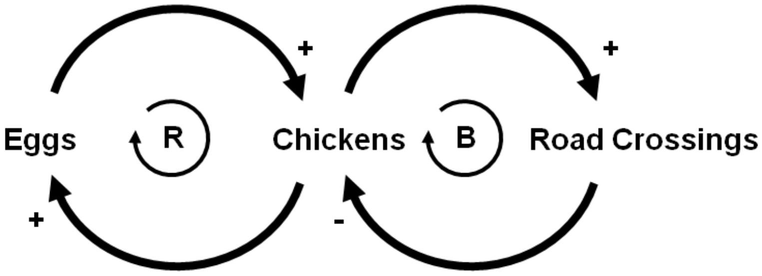
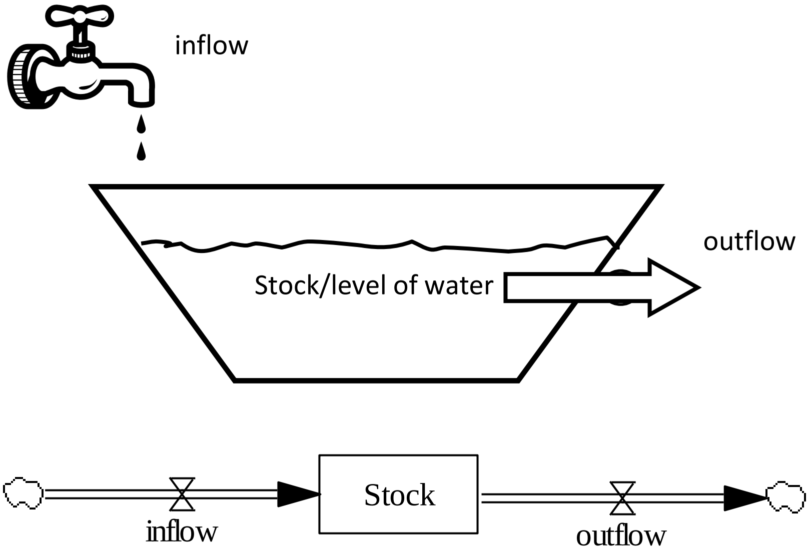


Figure 1: Eggs, chickens and road crossings.

While qualitative models are useful in describing the structure of a system and a dynamic hypothesis, most decision makers then wish to see some quantitative results. Here the approach is based on linking differential equations but is presented to the user in terms of “stocks” and “flows” via a stock-flow diagram which keeps the model transparent and easy to understand.

Stocks are accumulations and are represented by rectangles suggesting a box to hold the content. Flows may be inflow to a stock or an outflow from a stock and are represented by pipes with valves controlling the rate of flow into or out of a stock. Again taking the example from Sterman (2000), the hydraulic or bathtub metaphor is used to explain the concept and mathematics behind the simplest building block of one stock. Figure 2 shows the bathtub where the stock or level of water accumulates over time with inflow controlled by the tap and outflow by the plug. The system dynamic representation below shows the symbols used in VENSIM, one of the software platforms used for developing system dynamics models (others use very similar symbols). Underlying the symbols is the mathematical notation which shows how the stock is the integral of inflow-outflow starting with an initial level of stock. While the bath tub metaphor is easy to follow, it is easy to see how the stock could represent other systems such as population with births and deaths being the inflow and outflow from the stock of people.



$$Stock(t) = \int_{t_0}^{t} [inflow(s) - outflow(s)]ds + Stock(t_0)$$

Figure 2: The bath tub metaphor for stock and flow with integral equation

As stocks and flows are linked to other stocks and flows, a system structure develops and the system is described by a series of linked non-linear differential equations. Like all modelling, developing a good model is more like an art and part of the learning process is to develop the model along with stakeholders. Where this is not possible, then simple concept models are often useful to explain endogenous system behaviour and some system dynamicists prefer the use of small models over the more complex and detailed ones – see for example the discussion in Ghaffarzadegan et al (2011) who discuss the benefits of using small system dynamics models when addressing public policy issues.

The following sections review over 50 journal papers which have applied system dynamics to a transportation problem. The papers have been categorised as in table 1 which shows the category and number of papers included in the review. Each section does not review all papers in detail but does draw out examples of good practice which demonstrate the application of CLD or Stock flow models which provide something different to the more traditional transport modelling approach either in terms of insight or coverage of the problem. As this is a review it is not feasible to go into the detailed mathematics behind the stock-flow models, but readers may find this material within the papers quoted.

Application area	**Number of papers**
Modelling the uptake of Alternate Fuel Vehicles	12
Supply Chain Management with Transportation	6
Highway Maintenance/Construction	5
Strategic policy at Urban, Regional and National levels	13
Airlines and airports	10
Emerging areas	8
Total	**54**

Table 1 : Categorisation of papers by application areas.

3. Modelling the uptake of Alternate Fuel Vehicles (AFVs)

With the recent interest around the world in the promotion of alternative fuel vehicles such as Battery Electric, Plug-in hybrids and Hydrogen Fuel Cell vehicles, it is not surprising that modelling their uptake has been a hot topic in the application of system dynamic models. System dynamics is a good fit to this type of problem as previous studies have investigated technology or product diffusion in other sectors where the Bass diffusion model has been applied and adapted. Typically, the quantitative papers include such a diffusion process, a fleet ageing chain and a choice model for the purchase decision with varying levels of detail or market segmentation. Before going into the stock flow or quantitative models, Stepp et al, (2009) develop a CLD approach with stakeholders to investigate potential policy implications of supporting high efficiency vehicles. They consider consumer preferences, producer decision making, vehicle market dynamics and lifecycle environmental impacts including effects of production and recycling. An extract from their CLD is shown in figure 3 which they use to show the potential for "policy resistance" to purchase subsidies.

Implementing a subsidy for high efficiency vehicles in figure 3 reduces the market retail price which increases the share of high efficiency vehicles. This alone would reduce emissions, however as efficiency is increased then the demand for fuel is reduced which as shown in loop B7 reduces the cost per mile and therefore increases the vehicle miles travelled. This is the usual rebound effect. However as the market share increases then there is also a macro level effect on the price of fuel which affects costs per mile for other vehicles and increases miles driven per vehicle. This increase in vehicle miles driven may then impact on the scrappage loop R1, increasing the demand for new vehicles earlier which increases production emissions. Finally, the authors argue that the increased demand for high efficiency vehicles could via loop B1 (the demand-price effect), increase the price of such vehicles at least in the short term which goes against the intended impact of the subsidy. Whilst the actual outcome depends on the relative strengths of these loops or interactions, using such a diagram is useful in communicating the potential unintended consequences or policy resistance which may occur. The authors also discuss how policies which increase the cost per mile such as carbon taxes, may achieve synergy with such subsidies via the CLDs.

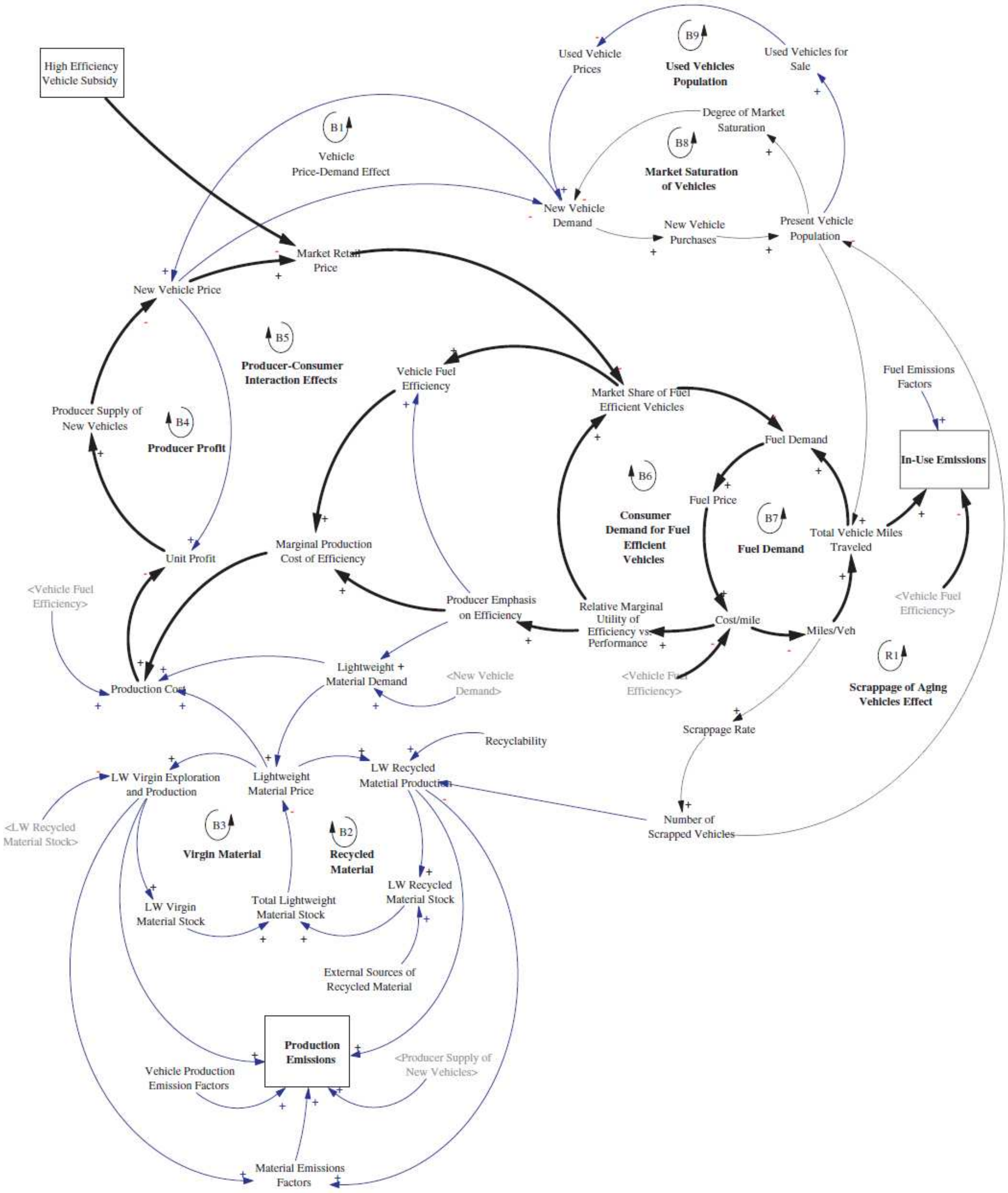


Figure 3: Example feedbacks in response to a high efficiency vehicle subsidy (Source : Stepp et al, (2009)

Moving on to the Stock-flow models, Struben and Sterman (2008) develop a framework for modelling the uptake of AFVs which consists of three main elements: a fleet turnover or stock model, a discrete choice model of the purchase decision and a social/technology diffusion process (figure 4). This process extends the Bass diffusion concept to include the impacts of word of mouth, marketing and social exposure to the new vehicles. It allows for a development of the choice set or willingness to consider the option over time including the effect of forgetting about the new vehicle types which then permits a failing market solution. This is an example of where system dynamics models can bring something different to the process of policy assessment – the possibility of an initial uptake of new technology which then fails and which has been observed in practice when subsidies for CNG vehicles were removed in Canada and New Zealand (Flynn, 2002). Whilst using an example of adoption of waste recycling, Ulli-Beer et al (2010) describe the general structures required to model acceptance dynamics involving paradigm shift involving endogenous preference and value change, these structures are useful in modelling acceptance and/or rejection of new technology in many areas.

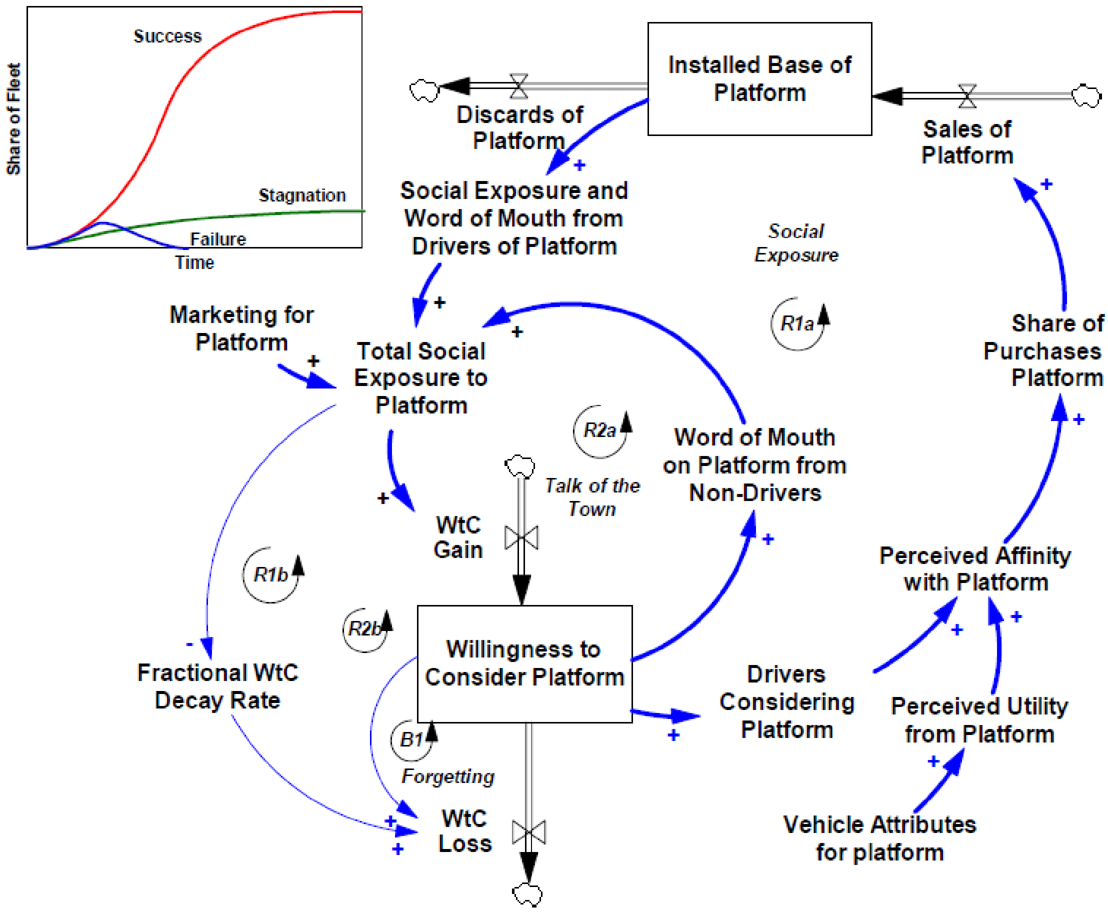


Figure 4 : Principal feedbacks conditioning willingness to consider new platforms and expected modes of behaviour (Source : Struben and Sterman (2008)).

Other studies incorporate similar diffusion structures but add other policy dimensions such as regulation, including manufacturer responses, Walther et al, (2010), add other indicators such as impact on fuel duty revenues (Shepherd et al, (2012) and the co-evolution of infrastructure for re-fuelling and extending to the cases of Natural gas, Jannsen et al, (2006) and Hydrogen Fuel Cell vehicles (Meyer et al, (2009) Kohler et al, (2010), Park et al,(2011)). Meanwhile others have investigated the role of strategic niche management, Kwon (2012), the implication of policies on distributional issues, Harrison and Shepherd, (2013) and applied similar diffusion models to the case of electric motorcycles in Taiwan, Trappey et al, (2012). In terms of impact of policies, most studies find that the uptake is not affected greatly by subsidies but more by regulation and infrastructure. However, as both Struben and Sterman (2008) and Shepherd et al, (2012) point out, the results may be more sensitive to the assumed strength of the word of mouth or marketing effects rather than to changes in the technical attributes of the alternate vehicles. This ability to bring in soft issues such as impacts of social exposure and to quickly demonstrate the sensitivity of results to assumed parameters are another strength of the system dynamics approach.

4. Supply chain management with transportation

Tako and Robinson (2012) provide a full review of discrete event and system dynamics applications in the logistics and supply chain context between 1996 and 2006. A total of 38 papers from 127 used the system dynamics approach which has a strong presence in the analysis of supply chains due to the natural ability to represent the well known "bullwhip" effect[2]. Of these 38 papers only a few investigate the impacts of supply chain management on the related transport system as shown in Table 1.

Sterman (2000) developed a generic SD model of the basic stock management structure which explains the sources of oscillation, amplification and phase lag which are observed in real supply chains. Georgiadis et al (2005) use these structures to construct a holistic model by linking single echelon models with similar structures to represent different elements of the supply chain. They apply the model to a case study of a fast food chain in Greece to investigate capacity planning under dynamic growth assumptions and the question of when to increase fleet size rather than lease extra capacity to meet delivery needs. The model is used to optimise the number of company owned trucks while minimising total transportation costs. Potter et al, (2008) investigate a similar problem. Variation in daily demands is made worse by demand amplification or the bullwhip effect and this can make it difficult for hauliers to judge investments in their fleet compared with how much to sub-contract. The paper confirms previous qualitative assessments in that demand amplification impacts adversely on transport costs and performance/efficiency. However, Potter et al, are also able to identify exceptions when vehicle capacity is just less than average demand, where an increase in demand amplification can improve transport performance. This is due to spare capacity being available within the transport system; however this strategy comes with penalties incurred as extra vehicles are needed to deal with average demand.

Disney et al, (2003), Otto et al, (2003) and Wilson (2007) use the SD approach to investigate the potential for dealing with the bullwhip effect by using the Vendor Managed Inventory approach. Figure 5 shows a typical supply chain where times to respond and estimates of demand for orders vary along the chain. Under the VMI approach the warehouse now acts as a distribution centre and the tier 1 supplier controls the order process from direct estimates of demand from the customer base. Information flows in the traditional approach between retailer and warehouse and warehouse and tier 1 supplier are effectively replaced by this direct connection to the customer which both improves accuracy of demand forecasts and reduces delays in the system. The rest of the supply chain is as in the traditional model. Wilson (2007) investigated transportation disruptions at each point along the supply chain. The most critical point was found to be between the tier 1 supplier and the warehouse, and this was therefore seen as the most important point in the supply chain and as the place to start with risk management strategies to mitigate the effect of transportation disruptions. The simple approach to management of inventory by changing the information flows was shown to reduce demand amplification and as Wilson (2007) shows VMI can be used to protect against severe transportation disruptions. VMI protects the retailer against the disruption and they do not suffer a peak in inventory, sharing information essentially smooths out the disruptive effects. The application of SD to this type of problem including transportation was a natural extension of the more traditional SD literature on supply chain or stock management.

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[2] Bullwhip effect refers to a trend of larger and larger swings in inventory in response to changes in customer demand, as one looks at firms further back in the supply chain for a product.

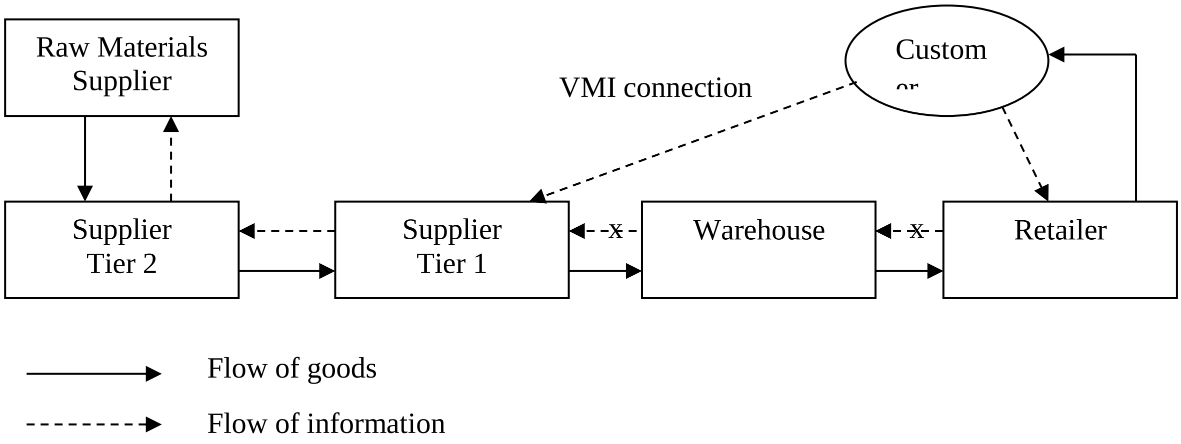

Figure 5: Supply chain management structure with VMI connection (adapted from Wilson (2007))

5. Highway Maintenance/Construction

There are five papers which deal with the highway maintenance and construction problem. Chasey et al (2002) and Fallah-Fini et al, (2010) model the impact of deferred maintenance on a highway system. Figure 6 adapted from Fallah-Fini et al, shows the aggregate feedback loops between deterioration and maintenance. The pavement condition deteriorates due to load factors and climate etc. The balancing loop B1 (Maintenance Fix) shows that budget allocated to maintenance operations increases the highway improvement rate which then decreases the area of highway under distress which then balances or reduces the desired maintenance budget. The reinforcing loop R1 (Accelerated Deterioration), includes the effect of maintenance budget shortfall which causes a delay in maintenance which increases the highway deterioration rate counter-acting the balancing loop. Whilst the physics of road deterioration and maintenance are complex in nature, the corresponding feedback structure is relatively simple. Fallah-Fini et al, developed a dynamic micro-level simulation model of highway deterioration and renewal processes. The model is calibrated with data from eight road sections in Virginia. The model is then linked with an optimization module to improve maintenance operations. The analysis results in different priority setting schemes that improve on current maintenance practices at both the project and network level. The approach suggests moving towards less costly preventative maintenance rather than more expensive (deferred) corrective maintenance should bring in benefits to the system as a whole. Again a move away from the traditional approach to the problem provides insight and promotes alternative strategies.

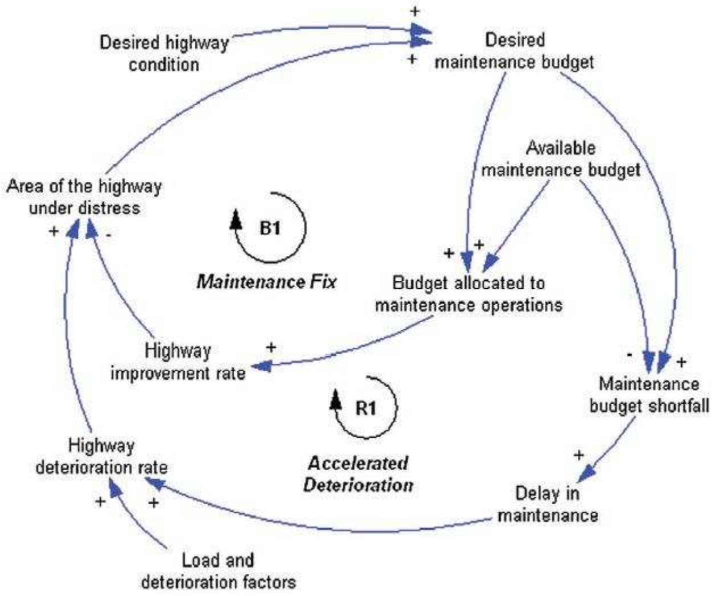

Figure 6 : Highway deterioration and maintenance causal loop diagram. Source : Fallah-Fini et al (2010))

Friedman (2006) however, questions the preventative maintenance policy. Friedman models the effect of road conditions on accident development and uses data to demonstrate that the mental model behind the policy of maintaining better roads to reduce accidents could in most cases be increasing accidents due to increased speeds and polishing effects. A more complex mental and stock-flow model is developed which better fits the evidence of increased accidents with increased pavement service index after maintenance. This demonstrates the importance of setting boundaries when viewing problems and the importance of evidence to support the mental models of basic decisions. Friedman questions the current mental model held within the road authority and demonstrates the importance of accounting not only for empirical evidence but also for the reasoning by decision-makers who develop their own mental models of short term consequences where data is missing.

The other two papers in this area relate to policy in China. Hang et al, (2011) develop a model to investigate the potential role of truck weight regulation policies for a region in China. While it includes a fleet turn-over model, it does not make much use of other system dynamics features. However, the paper claims to bring insight which other models do not e.g. that adjustment to a rigid policy (which requires a change in trucks) needs time and the disruption causes more problems to society than a more moderate approach.

Xu et al, (1998) develop a system dynamics model to investigate the cost overrun problem in Chinese highway construction projects. The existing policy was described as maximising quantity over quality in terms of building many roads at low cost with an average life of only 15 years compared with 40 years for Western Europe. The model shows that as demand for roads grows then the pressure to complete on time and allocation of budget between capital and maintenance costs meant that quality was reduced as a result of the system itself. This was due to the funding mechanism for new roads as revenues come from completed projects via the road users. This meant that there was a pressure to build faster with lower quality so that more revenue could be generated to fund more roads. A new equilibrium of project starts evolves but with a lower quality. The study showed that this problem can be overcome with loan financing and increases in user charges which releases budget constraints and hence pressures on the construction process to deliver on time (but with reduced quality).

6. Strategic policy at Urban, Regional and National levels

This section includes studies of high level or strategic policy at the urban, regional, and national level. Firstly, there are a number of models which look at implications for the structure of cities and regions as the economy, population, migration, infrastructure and land use interact with transportation. A sub-set of these build on the tradition of land use interaction models (LUTI). A feature of land use transport interaction is that these two systems operate on different time scales. Transport users may respond relatively quickly to changes in transport policy or costs, typically within months while the land-use system includes a significant degree of inertia. This is due to the fact that land-use in urban areas depends on physical structures such as buildings and transport infrastructure. This time dependence between the systems make it ideal for a system dynamics approach. Despite this most LUTI models are based on the traditional approach in transport modelling i.e. the notion of equilibrium and are static in nature. These equilibrium based models are used to forecast changes in transport demand and land use twenty or thirty years hence with no real connection from the current conditions to those future projections. The pathway to the future state is therefore unknown.

Pfaffenbichler et al, (2010), Pfaffenbichler (2011) introduce the concepts underlying the MARS LUTI model. They cover validation and transferability between cities and provide some examples of the model applied in practice. The model has now been applied in more than 20 cities world-wide and has been used as a training tool for planners and practitioners in Asia and in optimising strategic transport policies for a range of cities/regions. The model is seen as a departure from the norm in transport planning yet has proved to be a useful tool at the design stage. In particular the model was first of all designed using a causal loop analysis. One example concerns the link between planning decisions about infrastructure (road capacity) and the symptom of congestion. A simplified view of the CLD reported in Pfaffenbichler (2011), is shown in figure 7 along-side one of the common two loop Archetypal Structures from Wolstenholme (2003) which represents short term fixes which fail. The left figure shows the common archetype where a short term fix to a problem then fails due to some unintended consequence which causes the problem symptom to grow after some delay. Usually the positive reinforcing effects are outside of the system boundary considered. The right hand side shows the case for congestion which in the past has been solved by planners with increased capacity which then increases the attractiveness of car use which in turn increases congestion again. Pfaffenbichler (2011) provides a more detailed version of this concept and demonstrates that real world behaviour follows this pattern with evidence of traffic flows as infrastructure is developed for cases in Austria over a period of more than thirty years. A similar argument is developed for the interaction between infrastructure for cars and the emergence of urban sprawl. The MARS model has been applied in various studies to investigate optimal integrated transport and land use strategies (see references within Pfaffenbichler et al, 2010) where impacts are assessed more rapidly than with traditional models. It has also been linked with a fleet model by the same author called SERAPIS so that choice of car as technologies change may also be studied (Pfaffenbichler et al ,2011).

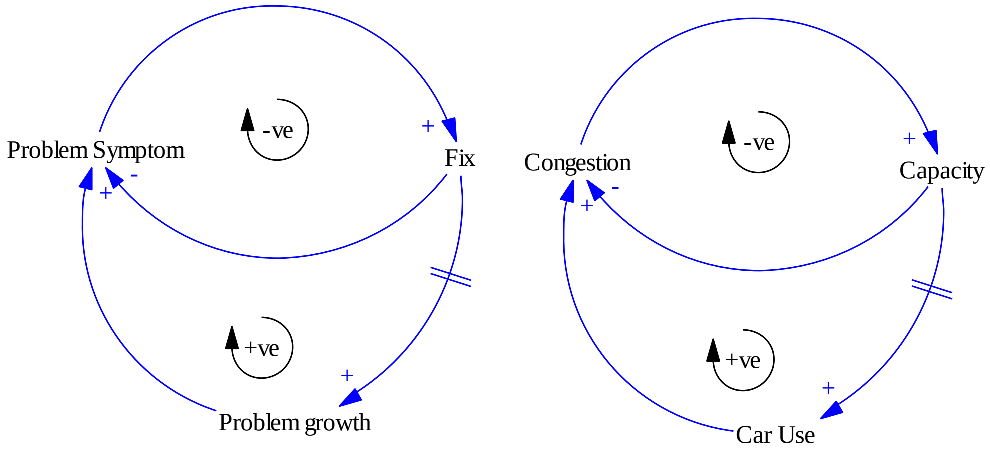

Figure 7 : Fixes that fail archetype and “congestion – capacity – car use” problem

Along similar lines, Haghani et al, (2003a) present a regional model based on an analysis of causal relationships and a feedback loop structure connecting a large number of physical, socio-economic, and policy variables. The model is made up of 7 sub-models: population, migration, households, employment, residential and commercial development, travel demand, and traffic supply or congestion effects. The model was programmed in the DYNAMO simulation language, and based on data from Montgomery County, MD. The model is well documented and includes calibration analysis using historic data from 1970-1980 validated against 1980-1990. Hagahani et al, (2003b) then report robustness and sensitivity tests covering inputs such as birth rate and regional economic growth rates. The model was used to assess the impacts of highway capacity expansion and the related changes in land use which in turn affected demand and the performance of the transport network.

Shen et al, (2009) develop a high level model comparing low/high density land use policies for Hong Kong. In the distant long term they show that compact high density scenarios are more sustainable with investment in rail based transport over car infrastructure which is seen to be more prominent in the low density case. The growth in population in the very long term can only be accommodated in the high density scenario so the authors conclude : "that only by means of a planning policy scheme to support compact and high-density development could Hong Kong meet the environmental, social and *economical requirements of sustainable land use and achieve a perfect balance among them."*

Wang et al, (2008) again develop a very high level interaction model between population, vehicle ownership, environment, GDP, travel demand and infrastructure supply, applying it to a case study of Dalian, China. Car ownership policies are studied and the wider system effects mean that strict ownership controls results in a larger city with a greater GDP and greater share of public transport. It is noticeable that by 2050 the interplay between population, car ownership, congestion, pollution and GDP mean that there are a similar number of vehicles in total but for quite different populations. Cities with vehicle ownership encouraged have a population of around 3 million versus 9 million inhabitants where ownership is not encouraged, however it appears that the larger city has a lower GDP per capita.

Feng et al, (2009) propose a hybrid model which integrates system dynamics, cognitive maps, and a sensitivity model to study the problem of investment in transport systems and in particular the question of resource allocation over time or when to invest. A case study for Taipei is used to illustrate the approach to satisfying the needs of multiple stakeholders. The results of the sensitivity analysis revealed that the increase in private vehicle trips caused increases in emissions, energy consumed and accidents and so failed to meet the competing needs of multiple stakeholders. However, the system is shown to be insensitive to managers' decisions on resource allocation timings i.e. delays to implementation are not the problem. Policies which control the growth in car use are shown to be the most effective at meeting the needs of stakeholders.

All the above studies deal with short term policies which have long term impacts on urban form or infrastructure and vice versa. System dynamics is ideal for investigating such systems which contain feedbacks and delays which are often outside of the mental model of the decision maker or where feedbacks cross stakeholder boundaries. Pataki et al (2009) take the interaction one step further and include the impact of forests. A multi-disciplinary study which used mediated model building over a period of six months to build a model of the transport and eco system of fossil fuel emissions is reported. The team conducted a whole ecosystem study of the role of climate, urban expansion, urban form, transportation, and the urban forest in influencing net CO_2 emissions in the Salt Lake Valley, Utah. The study showed the importance of the positive feedback between urban developments and investment in transport infrastructure. Emissions were seen to increase as this feedback created higher densities and increased traffic. The results suggested that a strategy of doubling the density of tree planting would not have a significant impact on total urban CO_2 emissions, while land use and transport policies which combine to reduce urban sprawl could produce a 22% reduction in CO_2 emissions by 2030 compared with the business as usual scenario.

Continuing with the theme of policies aimed at reducing environmental impacts, Han et al, (2008) investigate emission reduction policies for the Inter-city transport problem. Sensitivity analysis showed that reduction in CO_2 is best achieved by increased development of the railway network, but with a reduced emphasis on highway extensions and by imposing increases in fuel taxes. Piatelli et al, (2002) study carbon taxes in the context of freight in Germany. Their model covers investment in infrastructure, road, rail and waterway, subsidies, fuel costs and carbon taxes. Carbon tax is shown to have only small impacts on mode share and raising tax on all fuels actually increases the road share due to the relative costs of fuel by mode giving the counterintuitive result that a negative carbon tax for freight movements would reduce road share. Carbon tax simply increases revenues raised which could be used to reduce CO_2 by other means but the study suggests that investment in infrastructure for rail is better than a carbon tax, but even this has only small impacts on mode shares.

Egilmez et al, (2012) also aim to reduce CO_2 (in the USA), and three potential strategies are tested with different levels of intervention: fuel efficiency, public transportation and electric vehicle usage. Figure 8 gives an overview of the Stock-Flow diagram for their model showing the links between population, GDP, wealth, vehicle stock, vehicle miles travelled, congestion, emissions, highway capacity and land use. Population and GDP growth rates are exogenous while other equations are given in detail in the paper. The results showed that to be successful, some hybrid of individual policies was crucial. All three policy approaches are required to meet the CO_2 targets in the USA – 2 alone is not enough – three are needed with at least two of them at the 2nd level of implementation/success i.e. most optimistic. The authors also recognise the need to change the objective from a traditional CBA approach to one which accounts for sustainability if policies are to be adopted. This links nicely with a more general system dynamics model of policy resistance to change, Harich (2010); which discusses how social forces which favour change are inter-linked with those which favour resistance to change and that a proper coupling is required to understand why certain policies are ineffective.

European wide models have also been built to investigate EU wide transport and economic developments. Fiorello at al, (2010) provide an overview of the ASTRA model. ASTRA links transport demand, the economy, with the vehicle fleet and environmental impacts calculated for the European level. ASTRA has been used over the past decade to inform the European Commission about the impacts of European transport policy especially over a long time horizon, providing evidence for the White Paper on Transport. It is often used in conjunction with other models also developed using a system dynamics approach, such as the world energy model POLES and the fleet development model TREMOVE. It is encouraging to note that whilst traditional models such as the four-stage transport model still dominate the market in terms of research and application areas that clients such as the EU are taking note of other approaches such as these based on a system dynamics perspective.

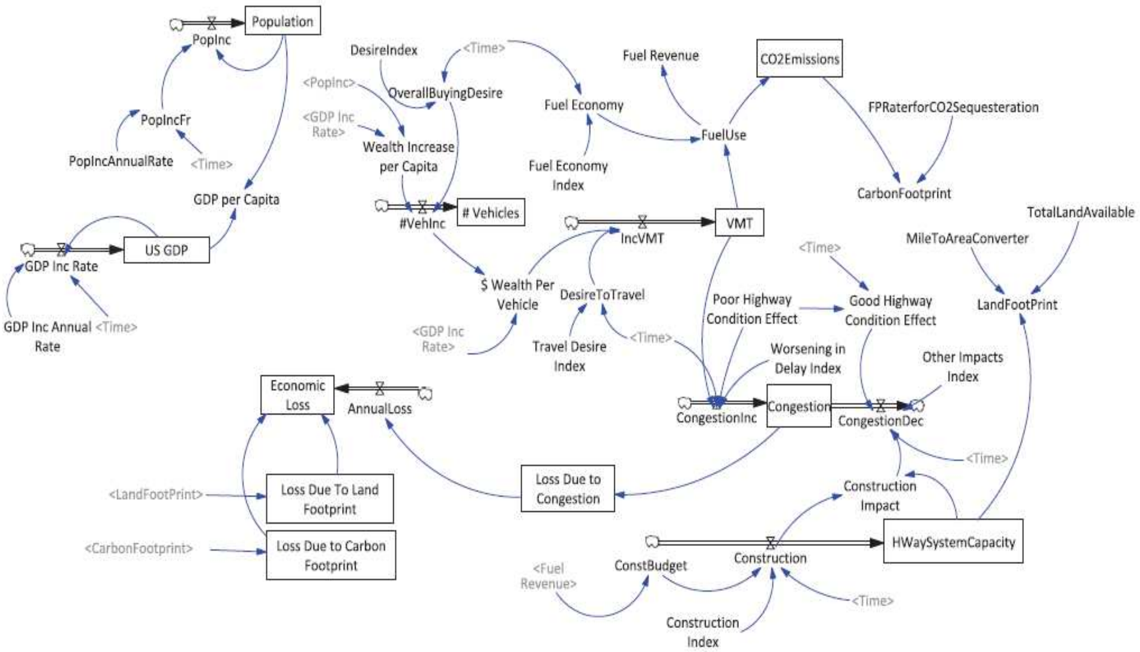

Figure 8 : Stock-Flow diagram of the high level model (Source : Egilmez et al, (2011))

Finally within this section the policy of road pricing is studied by Shepherd (2013) who firstly shows that a standard goal seeking structure from system dynamics is equivalent to transport dis-equilibrium modelling approaches in developing a simple model of competing toll operators. Shepherd then shows how estimating response elasticities during periods of change or prior to a full equilibrium can lead to errors in the toll setting strategies and cause instability and sub-optimal toll levels. Liu et al, (2010) develop a non-standard model of congestion pricing, combining linguistic and fuzzy preferences plus social networking effects to model mode choice. Figure 9 shows part of the model covering people's perception impacting on mode choice and the flow of revenues for reinvestment of toll revenue into the bus and Metro system which is modelled over time. This demonstrates how system dynamics can be used with other modelling approaches to provide a different angle or viewpoint for a common policy issue.

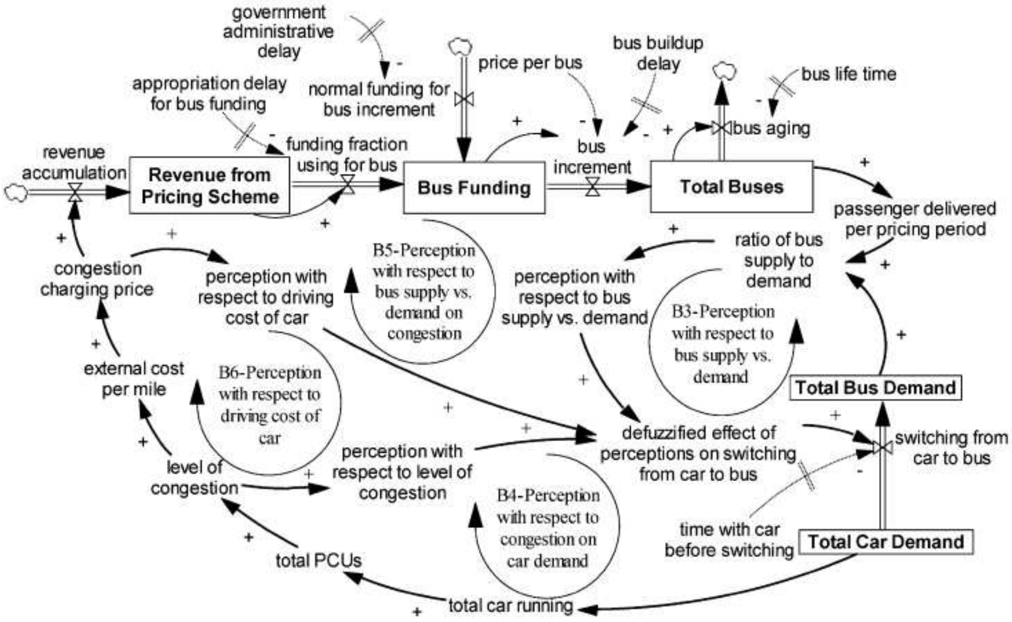

Figure 9: Effect of people's perceptions on the choice between bus and car, Source : Liu et al, (2010)

7. Airlines and airports

Liehr et al (2001) study the German airline market making use of data from Lufthansa. The aim of the model was to identify cycle generating components of the airline industry. It is well known that airlines aim to have high seat load factors so that they can maximize their profits. However the study showed that due to long aircraft lead-times and delays in recognising when there is an over-supply, the system begins to oscillate around the target seat load factor. Figure 10 shows the basic structure of the model which contains two delays and a negative feedback loop which can cause cycles even without external factors such as changes in GDP. Pricing strategies can only dampen the effects and not remove the cycles. Leasing and quasi continuous ordering policies were shown to dampen out the impacts of cycles. The study compared traditional statistical and static models with the SD model to improve acceptance of the model, but the dynamic model was the only one which could describe why the business cycles occur and therefore was deemed to be a better predictive model for out-performing the market when developing strategies for long-term capacity and fleet planning.

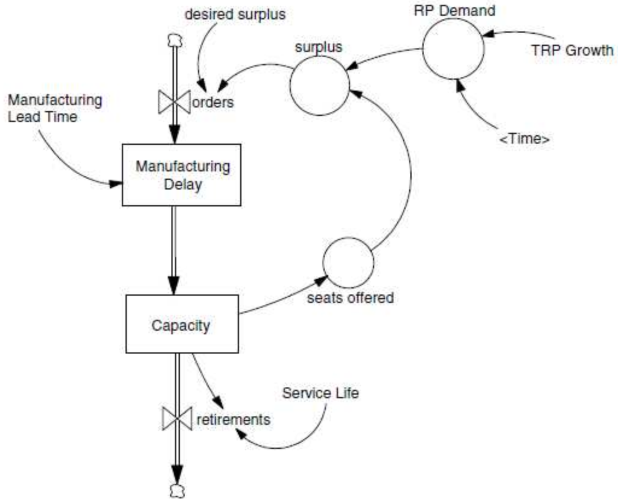

Figure 10: Basic structure of the airline market. Source Liehr (2001).

Lyneis (2000) also used the passenger jet aircraft industry to demonstrate the benefits of system dynamics models over traditional trend extrapolation and regression models. The structure of the industry is embedded in the model and so allows the model to predict cycles in orders of aircraft while the trend extrapolation approach overshoots the peak; and the regression model misses it completely. Compared with Liehr et al, Lyneis' model includes other reinforcing loops such as competing airlines all attempting to gain market share during the upturns which then results in overall capacity being overshot; the competition for new aircraft can lead to a longer lead time which then leads to the need to project further ahead which all combine to amplify the cycles.

Agusdinata et al (2002) develop a causal loop analysis of airline alliances covering the rush for globalisation during a transition economy, the impacts of congestion at hub airports, uncertainty and distrust and the potential for collaborative learning. The analysis is linked to the main literature in the air industry and the paper demonstrates how a CLD can be developed to explain complex behaviour within a cyclic market. The paper whilst useful for discussing market structure and responses, leaves the quantification of the model to future research.

Pierson and Sterman (2013) develop a model of airline industry profit cycles since de-regulation in the US. The model expands the boundaries of previous work and contains four main elements, endogenous capacity, demand, pricing and costs. The paper details the parameter estimation process and the use of Markov Chain Monte Carlo methods to establish confidence intervals. Contrary to prior work they show that the delay in aircraft acquisition is not as influential a determinant of the profit cycle as others have found and that price setting strategies were found to play a surprisingly important role in stabilising profits. These papers demonstrate the advantages of system dynamics approaches in that they are able to capture the cyclical market within the structure of the model which provides more useful insights to strategies to deal with cycles as shown in Pierson et al (2013).

Investment in airport runway capacity has been studied with a simple model by Miller (2005), Miller et al, (2007). While both papers use the same model, the better description is in the later paper. This paper develops and illustrates via a simple model a methodology for assessing the strategic value of air transportation infrastructure, in particular the benefits of being able to react swiftly to changes in the market. The model includes the influence of airport capacity on airline congestion costs which in turn affect the passenger fares and level of service, see figure 11. These factors then determine the aircraft per hour which in turn affect airport revenues. The model is used to assess different strategies for infrastructure delivery. These strategies include: the level of capacity increase, the time required to implement the capacity and the congestion threshold which triggers the need for additional capacity. Monte Carlo simulation is used to account for multiple sources of uncertainty. The model showed that a strategy of capacity enhancement based on small increments and shorter response times could yield greater benefits than strategies that consider larger capacity increases and which require longer response times. Future work could be to link to an air market model. The earlier paper, (Miller, 2005); combines real options analysis via Monte-Carlo simulation with the model. The simulation is used to evaluate when the option of building a second runway is greater than the real option of buying the land. In general it shows that when an inflexible investment has an NPV close to zero then the flexibility to delay or advance a project can be most valuable. The issue of when to implement large projects is something which is common in transport problems and system dynamics models are a useful tool in this area.

Suryani et al, (2010) extend this model to include impacts of population growth and GDP and the impacts on both runway and terminal capacity. The model is used in a scenario planning mode with optimistic and pessimistic cases. The difference in capacity requirements suggested that the runway may cope with demand for an additional 8 years in the pessimistic case, and factors such as level of service requirements can have a significant impact on the floor space required for the terminal. Suryani et al (2012) adapt their model to investigate air cargo demand and include effects of competition with other airports. This paper includes a validation of the model against historic data along with a scenario analysis with high/low growth scenarios to investigate when to invest in additional terminal capacity. A comparison with statistical extrapolation approaches suggests the low growth scenario is more probable but the authors suggest that the SD model is more useful as it includes the underlying structure of the problem and hence the possibility to understand the implications of a more optimistic scenario and the factors which influence the need for additional capacity.

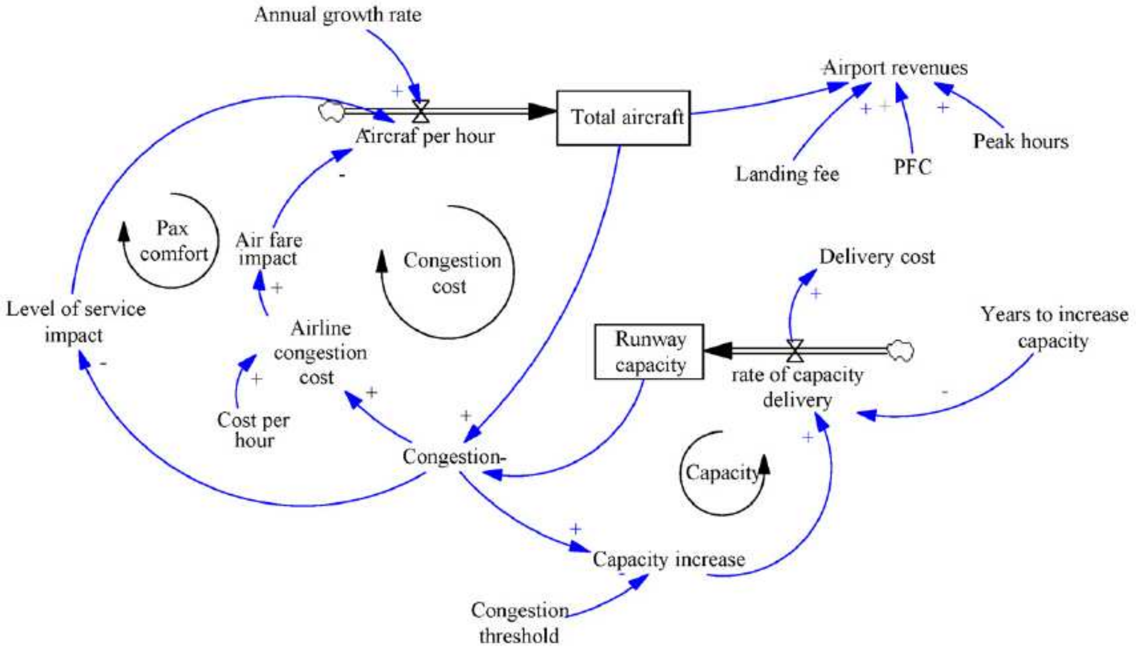

Figure 11 : Simple model of runway capacity and demand : Source Miller and Clarke, (2007)

Manataki et al, (2009) and (2010) report on a generic planning tool for airport terminal analysis. Whilst applied to a case study of Athens, the tool is designed to be generic and easily applied to other airport terminal layouts. Their aim was to bridge the gap between a very detailed operational analysis and a too aggregate macroscopic approach. The model splits the terminal into a series of functional areas and facilities and is able to capture interactions between these processes whilst allowing for random arrivals, delays, variations in schedule, capacity and levels of service as well as basic design parameters. The approach uses a flight simulator or GUI to facilitate what if scenarios for the planner/decision-makers. Finally, Sgourdis et al, (2011) present the Global Aviation Industry Dynamics (GAID) model which includes three sectors, passengers, airlines and manufacturers. The study examines five generic policies which aim to reduce the emissions of commercial aviation. Strategies investigated include, technological efficiency improvements, operational efficiency improvements, use of alternative fuels, demand shift and carbon pricing or market-based incentives. Each policy was implemented with three levels of effectiveness and combinations were tested and impacts on CO_2, revenue passenger-kms, profitability and average fares were recorded. An interesting aspect of the dynamics was the response to the highest level of carbon pricing where airline profits suffer initially, but as airlines shed aircraft in response they are then able to set higher fares and profits return to previous levels. This corresponds to real world behaviour seen when fuel prices were seen to double in 2008, initial disruption and some bankruptcies, followed by mergers which effectively reduced capacities were observed. It seems that due to the long timescales involved in the airline industry and in airport infrastructure coupled with changing demands that system dynamics has a lot to offer in this area and that more effort should be directed at such issues.

8. Miscellaneous/emerging areas

As transportation covers a wide area, it has not been possible to categorise some papers within the themes or areas identified above. This section includes some other application areas which are very specific or which may point the way to new emerging areas for the application of system dynamics in the transportation field.

At the more detailed end of the transportation spectrum, Mehmood et al (2003) apply SD to the area of car-following models. The proposed model assumed that drivers were capable of estimating the spacing between their own vehicle and the next downstream vehicle and rather than being based on drivers avoiding a collision, it is based on perception of safety. It does not include the lead vehicle's speed but does include status of brake lights. The model was calibrated and validated against field data and proved to work well for three vehicles. However it is not clear whether it would be practical to build a full micro-simulation model using this approach and a more standard micro-simulation approach which takes on board the model suggested may prove more useful in future work.

He et al, (2011) step up a level to investigate the problem of pollution around toll plazas in China. The authors combine a computational fluid dynamics model with a System Dynamics model of toll plaza operation to investigate the pollutants emitted under different assumptions about the penetration rates and capacity (number of lanes) for electronic toll collection technologies. The SD part was used to represent the queuing and service delays as vehicles go through the toll plaza. It was demonstrated that there was some interaction between penetration rate and number of lanes assigned to electronic toll collection which meant that pollutants may increase around the toll booths as more lanes are provided under certain penetration rates.

Changing mode, Macmillan et al, (2014) used participatory group modelling to from a qualitative model of the major Causal loops in the take up of cycling in Auckland, New Zealand. The loops included a safety in numbers effect which reduces the real and perceived injury rate as cyclist numbers increase. The model was populated with best available data and calibrated to recent historic trends. Policies to encourage cycling were modelled over a 40 year period demonstrating impacts on health, fuel savings and carbon emissions. It was meant to provide policy insight rather than falsely precise predictions and sensitivity tests were used to check for any parameters which either changed the ranking of policies or the order of magnitude of the outcomes. In this way the model was useful for exploring policy and model assumptions and provided a basis for discussions around cycling with others cities such as London.

Goh et al, (2012) develop two models to investigate policies to improve traffic safety. The first model is used to assess policy options which aim to encourage the purchase of cars with higher safety ratings. The second model is used to evaluate the impact of public transport policies on travel time and traffic safety considerations. The first model looks at how cars with different safety ratings are purchased and is similar to the work on alternative fuel uptake models, network effects and price effects being included. The larger the current share the more attractive it is to purchase due to lower maintenance costs and social norm factors. It was shown that high taxes and subsidies for low/high rated cars are needed to overcome the network and price effect. However, the sensitivity tests suggested that policies aimed at reducing the network effect e.g. awareness or early scrappage schemes for low rated vehicles may improve the fleet average star rating more quickly. The second model combined a goal based safety policy which reacts to number of crashes versus a tolerable level but then added the link between this and the policy on subsidies for public transport. It was shown that the larger the subsidy the greater the reduction in crashes and hence less need for other "safety" interventions which could be more expensive per saved crash. Similar to the work on the take up of alternate fuel vehicles, this paper demonstrates the importance of long term feedbacks and of taking a more holistic approach to the problem of safety.

Bivona et al, (2010) develop a case study analysis of maintenance policies for a city bus company. They describe the links between fleet maintenance, human resources and training as well as other key policies such as fleet renewal and how these may impact on service provision, customer satisfaction and overall profitability of the company. Two scenarios were developed to try and prevent the decline in revenues. The first was to cut all departmental budgets which while effective in the short term, was shown to be unsustainable in the long term. This is a classic use of system dynamics where performance measures are seen to get worse before then getting better. The second policy included some investment in new buses, which reduced the average age of the fleet, along with investment in training, all of which allowed increased service levels and was shown to be more sustainable. This paper showed how the system dynamics approach could be used with decision makers to help them move away from simple cost cutting policies to more sustainable policies which at first sight appeared to be counter-intuitive.

Mayo et al, (2001) report on a model for London Underground Limited who understood that to evaluate different restructuring options would require a holistic and integrated system-wide view of the Underground and its stakeholders. The model covered a range of stakeholders including the market or customers who had a choice of mode, a workforce module including morale, experience etc, suppliers, government and other private funding/finance. Aspects such as capital assets and maintenance played an important role. Profit motivation and investment levels could go into either virtuous or vicious circles depending on relative strengths of feedback loops. The model was used to look at re-structuring options for LUL. Asset management, staffing continuity and collaboration early on were seen to be crucial in the success of implementation of a Public Private Partnership and hard to reverse. The model was provided to the bidders to improve the tender process. The basic message to bidders from the model was that an Infrastructure company that maintains and invests appropriately in the asset base; maintains staff continuity; partners collaboratively with LUL and meets or exceeds the LUL specified performance targets will achieve significantly greater profits than one who does not. This paper provides a good example of a model used in practice.

Randers et al, (2007) in a similar vein as the air market cycles, explain shipping markets since 1950 as the interaction between two balancing feedback loops: a capacity adjustment loop which creates a roughly 20-year wave, and a capacity utilization adjustment loop which generates a roughly 4-year cycle. They describe how they persisted with a small model rather than use a detailed model and provided forecasts of when freight rates peaked. Shipping clients were at first distrusting of the model but senior executives were convinced by the simpler models and some of the client group trusted the forecasts to decide when to invest and when to get out of the market. Another example of real life impact and insight from a simple model which takes into account stocks and flows.

Finally, Yeo et al, (2013) develop a model of the impacts of port security on the competitiveness of the port. A causal loop diagram is developed with stakeholders and the quantitative model is used to explore the impacts of increased security which on the one hand increases attractiveness but on the other reduces it due to increased processing time and costs. Applied to a case study in Korea, the study suggests that a more optimistic approach to security would increase trade and prevent a spiral of decreasing competitiveness. Again the issue of feedback and policy resistance is key to understanding the issues and in explaining how a more controversial or less favoured policy may have the opposite impact to that expected by decision-makers whose mental model is unable to take these factors into account.

9. A note on calibration and validation.

Most system dynamics models are not designed to provide point forecasts but rather they are built to display the dynamic behaviour of the system under consideration. However being able to fit historic data brings greater credibility to the model and a lot of effort is now put into behaviour reproduction tests. Sterman (1984) reviews appropriate statistics for evaluating the historic fit of a model and points out potential pitfalls of using some standard RMSE approaches. The use of Theil's inequality statistics which decomposes MSE into three components of bias, unequal variation and covariation is recommended as it can be used to break down the sources of error. Fitting models to historic data is though only a part of model validation for a system dynamicist. Barlas (1996) discusses the model development and testing stages and emphasises other aspects relating to structure validity tests. Sterman (2000) also argues that validation of a model includes a number of important tests and that behaviour reproduction is only one part of the model validation process. Sterman (2000, p.858) discusses 12 tests in detail including structure assessment, parameter assessment, extreme condition tests, integration error and sensitivity analysis. The aim of the model building process is more to learn about the dynamic behaviour of the system and to improve confidence in the model.

Despite this, the software platforms do now include automated calibration tools to aid the estimation of parameters with the aim of improving historical fit. An example of this is described in Pierson and Sterman, (2013) described above where they make use of Markov Chain Monte Carlo methods to establish confidence intervals. Other examples where the calibration process is reported in detail and where models have been calibrated to historic trends and then validated against data from a later period include those by Pfaffenbichler et al, (2010), and Haghani et al, (2003a).

10. Summary

In the 20 years since Abbas and Bell outlines the possibilities for the application of system dynamics in transportation modelling, there has been a growing literature. Papers have appeared in some areas more than others, as seen in the recent surge in the modelling of uptake of alternate fuel vehicles. This is in part driven by the policy interest but is also an area which is well suited to the system dynamics approach as it makes use of existing structures such as the Bass diffusion model which has been applied to adoption of new technologies in other areas. This structure is easily linked with choice models and fleet ageing chains within the SD approach thus naturally accounting for time lags within the system. As predicted by Abbas and Bell, strategic policy issues at a regional or national level involving delays and feedbacks between different systems such as land use and transport have also been developed as an area where system dynamics has something to offer. Other areas which are well known for their dynamics such as business cycles in the air market or for delays in responses as in the supply chain area have also developed clusters of papers. The above review has outlined how the use of both more qualitative CLDs and quantitative stock-flow models have been used to provide new insights and explain the underlying structure within such systems. The approach often involves stakeholders in the development of the CLDs and the simple nature of the stock-flow approach aims at providing a transparent approach to modelling which is highly valued by stakeholders.

In the miscellaneous or emerging areas section, it was seen that some applications were not perhaps best tackled via system dynamics. For example system dynamics is not appropriate for the traditional network assignment problems, nor will it be able to replace micro-simulation tools. Whilst models can be formed with spatial elements by making use of subscripts or arrays, from experience it seems that once the number of zones increases beyond 200 then the model run times become a barrier and large models are then run in compiled mode. Thus while large models are feasible in this mode, it seems to go against the notion of a white box model and loses the benefits of communication to stakeholders which comes with the use of smaller faster models which demonstrate the dynamic behaviour of a system structure.

Instead the approach is better suited to providing a holistic system model which deals with feedbacks and delays between actors in the system. Future applications could look at competition dynamics, freight and the development of ports, sensitivity of systems and transport demand to changing external factors related to demographics and the economy and in modelling behavioural change whether this is at the user level of some higher level stakeholder. The approach allows transport models to be easily linked to other sectors such as health, climate, and the economy while taking into account time delays and feedbacks at different scales. However, it should be noted that system dynamics is not meant for precise point forecasts as Sterman summarises, "System dynamics helps us expand the boundaries of our mental models so that we become aware of and take responsibility for the feedbacks created by *our decisions",* Sterman (2002).

System dynamics should be used to understand and explore the nature of the problem and gives the modeller the opportunity to investigate general dynamic tendencies. The models can be used to test which parameters play a significant role in the stability and response of the system and the tools such as CLD and stock-flow diagrams enable a transparent approach to communicating results with stakeholders including the use of flight simulators and gaming tools which other approaches often lack. It is hoped that more transport modellers will in future work with the system dynamics approach and fulfil the aim of the international dynamics society which is to have a real world impact on business and policy. Finally, it is encouraging that clients such as the EU commission and local authorities such as Leeds in the UK are commissioning system dynamics based models to investigate their specific problems, having seen the advantages of communication with their local elected representatives.

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