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Simulating transport mode evolution: A system dynamics analysis of future trends and policy implications in NSW

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Abstract

This paper examines the use of system dynamics modelling to design effective policies for the urban transport system in New South Wales (NSW), Australia, which can help achieve emission reduction and sustainability targets. The study focuses on the ever-increasing growth of personal car use in NSW, which has led to increased energy consumption and air pollution. The system dynamics model considers the dynamics of urban transport mode choice through car or bus usage probability and identifies key factors affecting car utility, including GDP per capita, congestion, toll and fuel costs, and travel habits indicated by historically higher market share of cars. The simulation results suggest that, given the current set of policies, personal cars will remain the dominant mode of transport in NSW. However, increasing fuel prices by 30%, compared to its historical trend, can reduce the relative personal car utility and control the growth of kilometres travelled for personal cars. The study underscores the need for an integrated policy package that covers both supply and demand sides of the transport system to achieve sustainability goals.

Keywords: Transport Policy, Public Transport, Mode Choice, System Dynamics

1. Introduction

According to Transport for New South Wales (TfNSW), the number of personal car trips (vehicle driver & vehicle passenger) increased by 1.5% from 11,672K in 2009/10 to 13,523K in 2019/20, while public transport trips (i.e., bus & train) increased by 3.4% from 1,757K in 2009/10 to 2,460K in 2019/20. However, due to public transport's minimal share of total trips, its mode share in NSW increased only by 2% from 10.4% to 12.4% over the decade. In contrast, car mode share decreased only by 1% from 69.1% to 68.1% (Transport for NSW, 2020).

To encourage the use of public transport, the Australian government has invested in public transport infrastructure and services in major cities (Australian Government, 2021). Additionally, the government has introduced measures such as free public transport for seniors and concessions for students and low-income earners to make it more accessible and affordable (Department of Infrastructure, Transport, Regional Development, Communications and the Arts, 2022).

[I] This research was conducted while Hossein was a visiting scholar at rCITI, prior to joining BMC.

Urban transportation systems are characterised by their complexity, which stems from a multitude of interrelated factors. One of the main challenges is the high population density of cities, which leads to an increased demand for transport services, resulting in congestion and delays during peak hours. Moreover, the diversity of transportation modes available in urban areas, such as cars, buses, trains, and bicycles, each with its unique infrastructure needs, poses another challenge. Successful integration of these modes is essential for the seamless and efficient movement of goods and people (Gwilliam & Price, 2019). Managing and organising urban transport systems are complicated tasks involving various stakeholders, including local authorities, transport providers, and travellers, all with their particular requirements and objectives. Proper collaboration among these stakeholders is crucial to ensure the smooth and efficient operation of the system. However, political and economic factors can add another layer of complexity to the process by influencing transport policies and decision-making (Litman, 2020).

Overall, the complexity of urban transport systems arises from a combination of physical, operational, and institutional factors. Effective management of these systems requires a deep understanding of the interactions between these factors and the ability to balance competing demands and interests. Understanding the dynamics of the urban transport system requires tools capable of tackling the complexity of the transport sector. A systems approach that considers feedback loops, delays, and nonlinear relationships is crucial. One such tool is system dynamics modelling, which provides a valuable toolbox to simulate the impact of policy interventions and identify the unintended consequences of their actions. For example, the ASTRA model was developed to provide a tool for strategically assessing transport policies (Fiorello, et al., 2010). The authors noted that traditional transport policy assessments often fail to account for the dynamic and interconnected nature of the transport system, which can lead to unintended consequences and suboptimal outcomes. System dynamics modelling of the urban transport system in Australia, which has not been developed considerably so far, could provide policymakers with a toolbox to design the optimum combination of policies (on both the demand side and supply sides of the system), including fuel taxes, fuel efficiency standards, electric and/or low-emission vehicles, public transport infrastructure, etc. which is necessary to achieve the emissions reduction targets and other transport sustainability goals.

In this paper, the ever-increasing growth of personal car use in New South Wales (NSW) of Australia, which has resulted in more energy consumption and air pollution compared with the minor share of public transport in urban areas, is studied via a system dynamics model and the simulation results are discussed under different scenarios/policies.

This paper is organised as follows. The next section describes the research method, including research steps, tools, and data sources. Next, a conceptual framework of the urban transport system in NSW has illustrated in the form of causal loop diagrams; then, the quantitative simulation model is explained. After evaluating the model validity, the simulation results are described under some scenarios and policy recommendations are discussed at the end.

2. Method

System Dynamics (SD) is used as the main methodology in this research. First developed at MIT, SD is a valuable modelling and simulation methodology commonly applied for dynamic behaviour analysis and long-term scenario and policy investigations about complex problems (Forrester, 1961). SD is always used to investigate the structure that creates a complex problem's behaviour over time and to analyse and forecast the system's behaviour under different situations. It provides both qualitative and quantitative tools to model a given complex system and to capture the interactions between variables through nonlinear feedback causal relationships (Forrester, 1987; Sterman, 2000). System Dynamics has been applied in various fields, including environmental management (Liu, et al., 2020), public health (Currie, et al., 2018), construction (Suprun, et al., 2018), supply chain management (Golrizgashti, et al., 2023), global oil market dynamics (Hosseini, et al., 2021), renewables (Dianat, et al., 2022), and business-level problems (Hosseini, et al., 2020).

The main steps in this research are as follows (Sterman, 2000): I. Problem articulation; II. Dynamic hypothesis; III. Formulation (qualitative and quantitative simulation model); IV. Testing (verification and validation); V. Policy formulation and evaluation

The initial step involved a concise literature review and analysis of time series data pertaining to the urban transport mode choice dynamics in the NSW case study, to determine the problem boundary and establish the problem definition. Based on the findings from literature review, a hypothesis is formulated to describe the dynamics of transport mode market share over time. This hypothesis was then transformed into a qualitative model through the use of subsystem diagrams and Causal Loop Diagrams (CLD) to represent the problem's main structure. Utilising the qualitative model, a quantitative simulation model in the form of a Stock-Flow Diagram (SFD) was created, with relationships between variables based on time series data, derived from relevant reports published by Australian authorities[I].

In the next step, after verification and validation, the model was simulated under different scenarios, the results were discussed and policy implications were concluded.

It should be noted that the model used the system's historical data from 2010 to 2021; the initial simulation year is 2010, and the final year is 2030; scenarios were run from 2023; also, Vensim software is used here for the model development and simulation.

3. Simulation model

The dynamics of urban transport mode choice are captured through probability of car or bus usage over time[II], which is determined by a set of loops and relationships. As depicted in Figure 1(a), an increase in GDP per capita will result in more private car purchases, since it brings on more purchasing power for families. This, in turn, increases the average density and decreases the average flow. This congestion prompts the construction of more roads to alleviate the increased traffic. Additionally, factors such as tolls, fuel costs, and the historical prevalence of personal car usage (measured by car kilometres travelled per capita) impact car utility. Accordingly, the car utility is defined as a weighted average function of influential factors including the kilometres travelled per capita by car (which represents the habit of using cars versus buss), average fuel price, average toll fare cap per vehicle, and average flow of cars (which represents the congestion index). The bus utility is defined as a weighted average function of influential factors including the number of bus stops (which represents the bus

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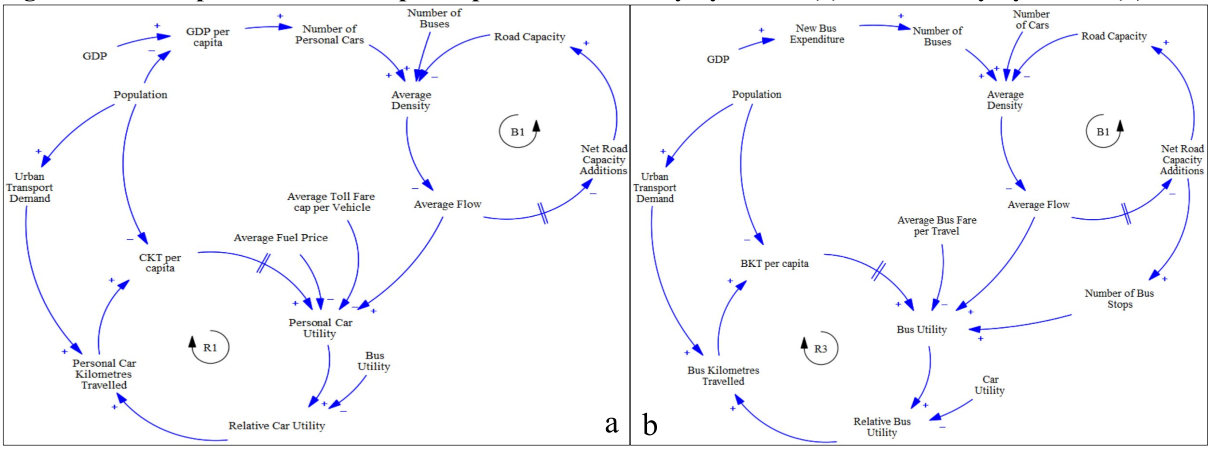
[I] These include:

- Motor Vehicle Census (Australian Bureau of Statistics (ABS), 2022)
- National, state and territory population (Australian Bureau of Statistics (ABS), 2022)
- Australian National Accounts: National Income, Expenditure and Product (Australian Bureau of Statistics (ABS), 2022)
- Survey of Motor Vehicle Use (Australian Bureau of Statistics (ABS), 2022)
- Australian Infrastructure Statistics and Transport Yearbook (Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2022)
- Retail petrol and diesel prices (Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2017)
- Public transport pricing (The Productivity Commission, the Australian Government, 2021)
- Toll costs by road (Transport for NSW (TfNSW), 2022)
- TfNSW Economic Parameter Values (Transport for NSW (TfNSW), 2022)
- Annual retail price for petrol and diesel (Australian Institute of Petroleum (AIP), 2022)

[II] It should be noted that we considered buses and cars as representatives for public and private transit modes and the model could be developed to include other urban transport modes in NSW.

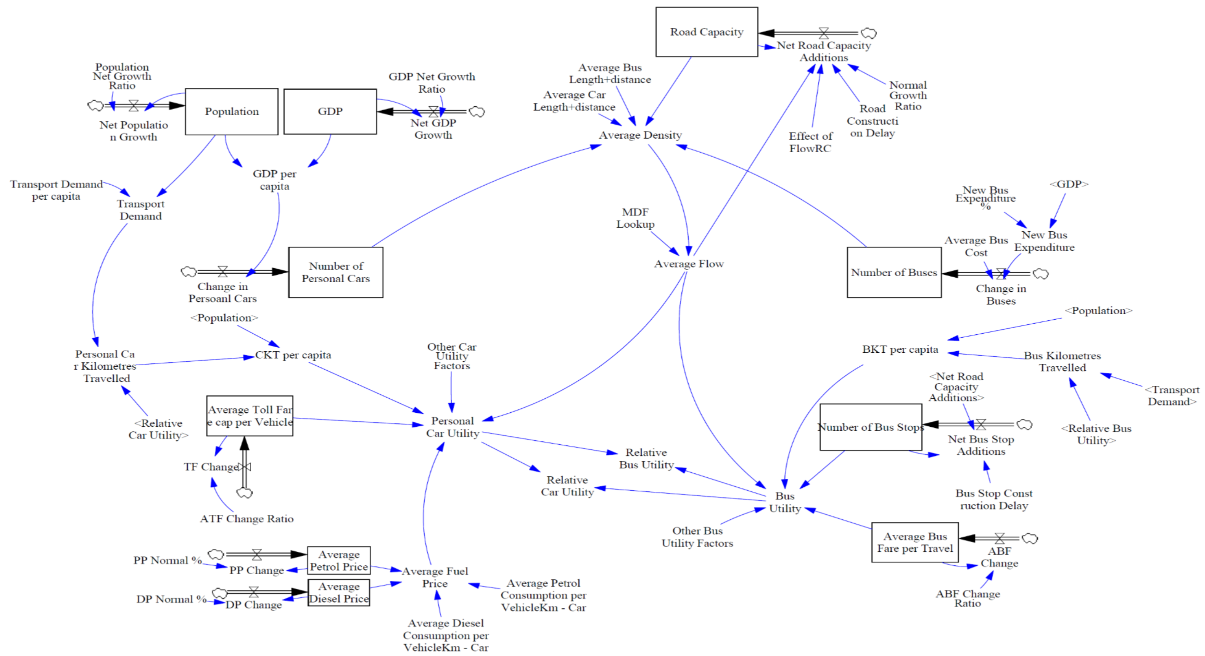
accessibility), average bus fares, and bus kilometres travelled per capita (which represents the habit of using buses versus cars).
Greater relative car utility leads to increased car usage, thereby closing the loop and further boosting personal car utility.
Figure 1(b) shows the dynamics of bus utility and the associated loops. An increase in GDP leads to more budget for the public sector, which can purchase new bus fleets. This, in turn, affect density, flow and road capacity, as discussed earlier. The Bus utility is determined by various factors such as travel fare, number of stops, congestion, as well as the historical popularity and utilisation rate in the urban transport system. A rise in bus utility leads to an increase in bus usage, ultimately closing the loop by enhancing the bus utility.

Figure 1: The loops and relationships for personal car utility dynamics (a) & bus utility dynamics (b)



Due to the limitations in the length of the paper, the description of the quantitative simulation model (including the equations) is not mentioned here although the structure of the simulation model is shown in Figure 2 as a Stock-Flow Diagram.

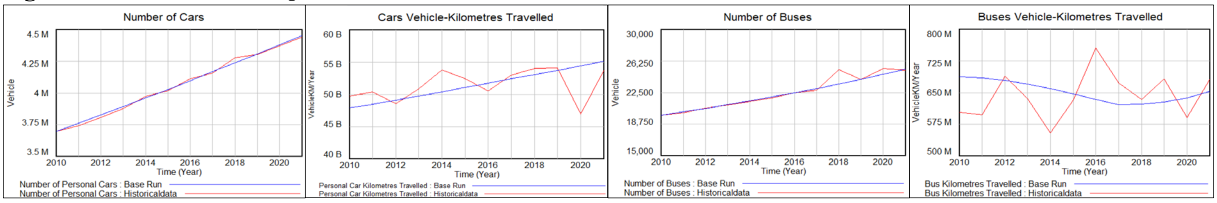
Figure 2: The model structure for urban transport mode choice in NSW



4.1. Model validation

The process of model validation entails running the SD simulation model for past time periods and verifying the given historical data can be accurately regenerated using the equations and relationships specified earlier. In the interest of brevity, only the validation test results are reported here. As demonstrated in the following figures, the simulation model can effectively replicate the historical data.

Figure 3: The behaviour reproduction validation test results



5. Results

5.1. Status quo

The following figure shows the change in the relative car and bus market shares over time. Although the relative car utility is decreasing and the relative bus utility shows a slightly increasing trend, the value of the car utility is relatively higher. Therefore, with the current policies in place, which assume business as usual, personal cars will continue to be the dominant mode of transport in NSW.

As it was apparent from Figure 5, historical data on the total distance travelled (Veh-Km) indicates that cars have been the primary mode of transport. However, based on the simulation result for the total kilometres travelled by cars and buses, it is clear that the trend of ever-increasing car usage will not even be stabilised. The value for car travel increases from 53.7 billion kilometres travelled in 2021 to 61.5 billion kilometres travelled in 2030, indicating a 14% increase. In contrast, the value for bus travel increases from 652.6 million kilometres travelled in 2021 to 951.4 million kilometres travelled in 2030, showing a 46% increase. These market share estimations are derived from the probability functions of cars and buses over time which are in the form of Logit functions of utility of cars versus buses.

Figure 4: Simulation results - car and bus relative market shares

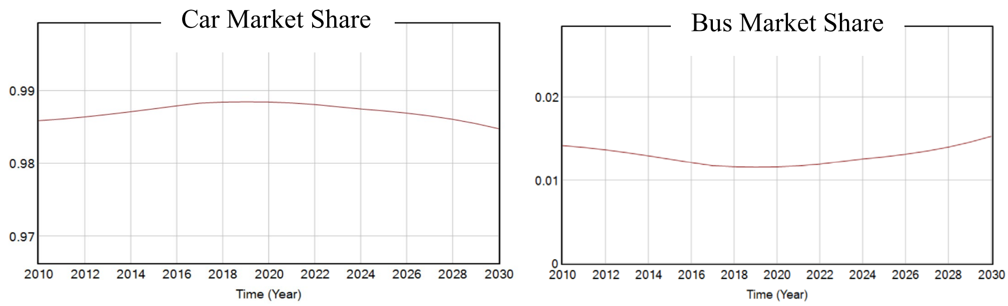
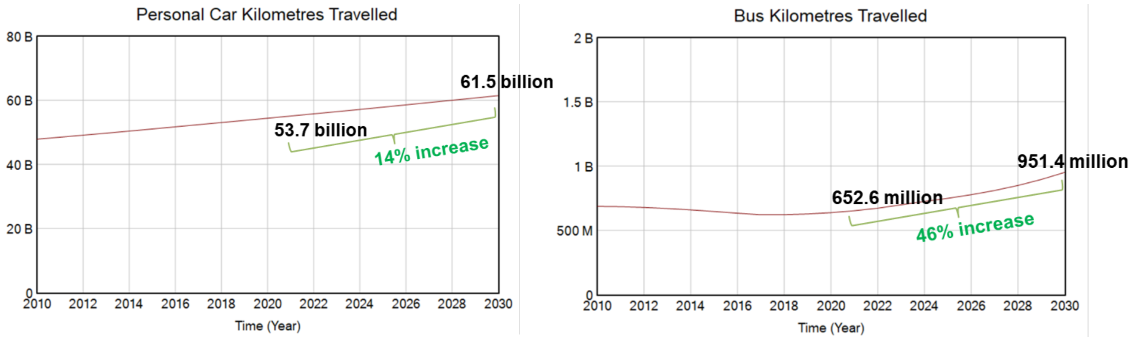


Figure 5: Simulation results - total vehicle-kilometres travelled by cars and buses (Veh-KM/Year)

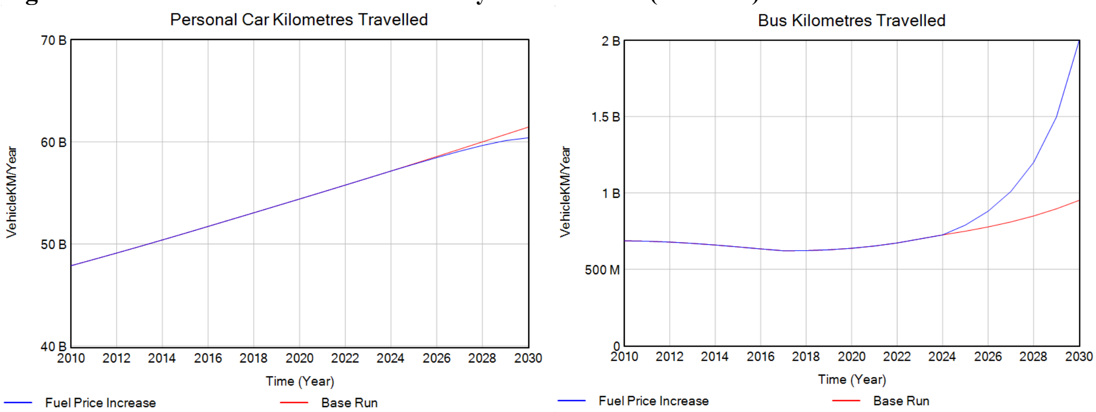


5.2. The impact of increase in fuel price

In this subsection, we simulated the impact of a fuel price increase, which is a significant factor affecting the utility of vehicles. The simulation scenario involves gradually increasing the average fuel price change rate from 2024 until it reaches 30% higher than the base run in 2030 for both diesel and petrol fuels. Based on the simulation results, the increase in fuel price causes a decrease in the probability of personal cars, leading to more kilometres travelled by buses. This results in a substantial adjustment to the growth rate of personal car usage over time, which is a noteworthy change in urban transport. In the new scenario, the number of kilometres travelled by buses is projected to increase from 951.4 M in the base run to 1996 M.

In this research, we considered buses as a representative of public transport and personal cars as the representative of individually owned transport modes. The simulation results reveal a gradual and slight change in variables that have a significant impact on the medium-term trend of urban transport mode choice behaviour. These variables possess leverage attributes that can influence the direction of the trend over time.

Figure 6: Total vehicle-kilometres travelled by cars and buses (scenarios)



6. Conclusion

This paper explores the potential of system dynamics modelling as a strategic assessment tool to transition towards sustainable transport modes. Specifically, the study focuses on the increasing growth of personal car usage in NSW, Australia. Using an SD model and real historical data, this paper showcases the applicability of System Dynamics approach to examine different policies and scenarios in order to increase the modal shift and to achieve emissions reduction and transport sustainability targets.

The results suggests that the current set of policies in NSW may lead to personal cars remaining the growing dominant mode of transportation, and only a hypothetical gradual increase of fuel price may result in stabilised car usage. Accordingly, the model results suggest that increasing fuel prices by 30%, compared to its historical trend, may help control the growth of personal

car usage and kilometres travelled. The results indicate that despite a slight increase in the utility of buses, it is necessary to invest considerably in supporting public transport to cover the transportation demand that is currently met by private transport.
The study highlights the usefulness of system dynamics modelling approach in capturing the variations and dynamic nature of demand and supply interactions of the transport system to achieve sustainable urban transport. However, it should be noted that this study considers only two transport modes of buses and cars. Future research can incorporate other transport modes such as trains, metro, active and shared transport modes. Furthermore, the presented model only considers the transport mode utility at a macro level. By considering subclasses of users' preferences and behavioural aspects such as lifestyle changes in future research, this model can better represent modal shift influenced by both supply and demand interactions.

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