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An Integrated DPSIR-SD Framework for Sustainability Assessment of Roads in Australia

Sneha Kaira [1], Oz Sahin [1,2,3,*], Anisur Rahman [1,2] and Sherif Mohamed [1]

[1] School of Engineering and Built Environment, Gold Coast Campus, Griffith University, Gold Coast 4215, Australia; sneha.kaira@griffithuni.edu.au (S.K.); a.rahman@griffith.edu.au (A.R.); s.mohamed@griffith.edu.au (S.M.)
[2] Cities Research Institute, Nathan Campus, Griffith University, Brisbane 4111, Australia
[3] School of Public Health, Faculty of Medicine, Herston Campus, The University of Queensland, Brisbane 4006, Australia
* Correspondence: o.sahin@griffith.edu.au

Abstract: The Australian Sustainability Development Goals (SDGs) Summit in 2018 attracted much-needed national attention towards environmental goals and targets compared with other aspects of sustainability. Road infrastructure is the backbone of modern society and plays a crucial role in accomplishing a targeted balance between these aspects of sustainability and achieving the SDGs. This article presents an integrated sustainability performance assessment methodology that acts as a decision support tool. A series of two conceptual modelling techniques—drivers—pressure—state—impact—response (DPSIR) and system dynamics (SD)—is employed, with the cause-and-effect relationships of the sustainability indicators developed utilising the DPSIR framework, and a quantitative analysis carried out through a subsequent SD model. The end result is the generation of a Sustainability Performance Index (SPI) for road infrastructure created by analysing the SD model and DPSIR index layer relationship. The benefits and applicability of the proposed methodology are validated through case study analysis. The overall aim is to determine restricting factors and response strategies influencing road infrastructure and transport sustainability performance during the operation and maintenance phase. Thus, a significant contribution is made through the proposed methodology for assessing factors influencing the long-term achievement of the SDGs.

Keywords: driver-pressure-state-impact-response; system dynamics; road sustainability; sustainability performance index; sustainability development goals; sustainable transport

Citation: Kaira, S.; Sahin, O.; Rahman, A.; Mohamed, S. An Integrated DPSIR-SD Framework for Sustainability Assessment of Roads in Australia. *Sustainability* **2022**, *14*, 7142. https://doi.org/10.3390/su14127142

Academic Editors: Mayca Rubio-Gámez and Fernando Moreno-Navarro

Received: 11 May 2022
Accepted: 6 June 2022
Published: 10 June 2022

1. Introduction

Recently, there has been a rise in several factors exerting multi-faceted impacts on road infrastructure sustainability performance, such as changes in travel patterns, loss of toll revenue, GHG(CO_2-eq) emissions and budget constraints (road operation and maintenance costs) [1], driven by factors including population growth, climate change and epidemics such as COVID-19 [1]. To deal with such dynamic scenarios, the concept of a 'sustainable road' has emerged, defined as a road that is (i) constructed to reduce social and environmental impacts; (ii) designed to optimise alignment; (iii) resilient to future environmental and economic pressures (e.g., climate change and resource scarcity); (iv) adaptable to changing uses, including increased travel volumes; and (v) able to harvest its own energy requirements [2]. Therefore, there is an additional need for governments, road authorities, and civil road contractors to be innovative in identifying these facets' negative and positive effects on the quadruple bottom line of project sustainability (economy, environment, society, and governance) [1]. Furthermore, the project planning phase is the most critical of all the lifecycle stages because the risk of project failure is directly affected by the effectiveness of the initiatives taken [3]. Therefore, it is also essential to integrate sustainability initiatives during the project's planning phase. Consequently, the negative impacts of physical infrastructure on sustainable development are minimised, and the value-added from the investment in the project is maximised.

A brief discussion on the significant drawbacks of the available sustainability assessment methodologies was carried out in the early part of this research study [4]. As a result, the study ascertained that the system dynamics (SD) approach is the preferred method for comprehending the importance of a dynamic perspective for the quadruple bottom line during sustainability assessment [4]. This article divides the SD approach into three phases: preliminary analysis, specified analysis, and comprehensive analysis [5]. In the preliminary analysis, the understanding of system characteristics is deepened. The research's preliminary analysis includes defining the key sustainability indicators and developing their causal feedback loops. In brief, this step involves both qualitative (casual loop diagram) and quantitative (stock and flow) structuring of the sustainability indicators. To support the preliminary analysis, utilising an analytical framework such as DPSIR (—driver-pressure-state-impact-response) guides the conceptual modelling. Further, DPSIR helps capturing critical influencing factors on project sustainability and set the boundaries for this problem.

Based on the preliminary analysis results, the specified system structure analysis is quantitatively carried out via the coefficients and equations in the user interface of Vensim® DSS 9.1.1 version software. Finally, the simulation results from alternative project options are compared in the comprehensive analysis. This research article aims to develop a comprehensive Sustainability Performance Index (SPI) for project options considering dynamic aspects of sustainability. SPI development utilising an integrated SD-DPSIR framework also aids in identifying the interrelationships among sustainability aspects and creates confidence that the study bridges a research gap.

This article is organised as follows. First, a literature review on the sustainability of roads and the prerequisites of assessment methodologies are introduced in Section 2. Next, Section 3 briefly illustrates the selected research approach and discusses the relevance of the selected sustainability measurement criteria and indicators. Then, the applicability of the research methodology is validated through case study selection in Section 4. Finally, a brief discussion of the results of the SPI for the selected project is carried out in Section 5, while the conclusion and future recommendations are provided in Section 6.

2. Literature Review

Roads and other public infrastructure projects catering to a multi-stakeholder system present a higher-order complexity in defining sustainability problems and exploring solutions [2]. There is a substantial body of literature focused on developing sustainability assessment frameworks. Several groups have studied the application of sustainability evaluations during different phases of roadway projects using various methodologies. The relevant literature was reviewed in the early part of this research study to identify gaps in the sustainability evaluation frameworks for infrastructure systems [4]. Unfortunately, the previously mentioned studies do not address the prerequisites that are strictly related to the sustainability development orientation of the methodologies below [6]:

- Adopting a holistic approach;
- Moving from multidisciplinary and interdisciplinary towards transdisciplinary approaches;
- Adapting a normative function;
- Promoting social learning and mutual feedback;
- Dealing with uncertainties and scenarios.

While some studies focus on the environmental aspects of sustainability, these are mainly related to pavement material selection [7,8] or pavement maintenance strategies [9]. Other studies only analyse the cost components associated with sustainability indicators during project evaluation [10]. Though some studies incorporate indicators from three areas (economic, social and environmental) of sustainability, their assessment approaches lack consideration of the conflicting and dynamic nature of indicators at different project lifecycle phases [11,12]. Certain studies concentrate more on analytically comparing sustainability-related (GHG(CO_2-eq) emissions, fatality rate, economic costs, noise emissions abatement) performance analysis of roundabouts and intersections [13,14]. Though such studies conclude that modern roundabouts are far better in enhancing sustainable design with reduced emissions, stopping time and fatalities, they are still limited to discretely assessing sustainability criteria. As sustainability development is nothing but balancing economic, social, environmental, and governance aspects, it is also necessary to identify the dynamic interrelationships among them. At the same time, other studies concentrate on organisations practising sustainable procurement by incorporating various aspects of sustainability [15].

Moreover, one of the essential features of road sustainability assessment is addressing the system boundary [16,17]. For example, considering road geometry and access issues and pavement maintenance and rehabilitation activities is essential during road operation and maintenance phase analysis. Other researchers and academic reviews may also include a brief analysis of the many available rating tools and their limitations for transportation infrastructure sustainability [18,19]. Despite the shortcomings of current sustainability assessment tools and methodologies, they are still valuable in this research study. They tend to inform the current state of practice towards more sustainable solutions because they encourage incorporating sustainable development principles.

This study also identified that 'sustainability criteria' are essential in measuring sustainability performance and analysing attributes under each dimension/aspect [20]. At the same time, the objectives of each criterion are fulfilled by the corresponding indicator analysis [20]. A vast list of indicators for criteria analysis is available in the literature. In general, academics identify the degree of importance of respective indicators and select those that fulfil their research objectives. Then, an expert survey is carried out, assigning Likert scale values to rank indicators based on their importance [21]. However, this approach is considered weak as it is based on individuals' opinions and perceptions.

Moreover, qualitatively analysing the intertemporal comparisons between criteria/indicators is impossible [6]. For example, the impact of sustainability criteria during the project construction phase are different from those (benefits and costs) during the operational phase and are difficult to distinguish using a qualitative approach. Numerous authors used the fuzzy logic membership function to counter these drawbacks. In the membership function generation procedures, experts use various predefined forms (triangular, trapezoidal, bell-shaped, S-shaped) to fit the statistical/historical data based on their analysis and experience. However, membership evaluation is also an open problem [22,23]. In most cases, the actual data do not strictly follow these forms, resulting in extensive loss of information. Hence, an extraction of the basic form of the membership function remains a dilemma.

Further, qualitative analysis has no analytical techniques, such as discounting to compare impacts occurring across different years [24]. Contemplating the drawbacks of the methodologies, this research article selects sustainability aspects and associated criteria from Australia's Infrastructure Sustainability (IS) rating tool, as shown in Section 3. The selected indicators under the criteria are utilised for analysing the project's sustainability performance, thus avoiding problems aligned with indicator selection. The IS rating scheme is a tool used by the Infrastructure Sustainability Council of Australia (ISCA) to improve the productivity and liveability of industry and communities considering the sustainability of infrastructure. In the IS rating tool, each criterion is assessed as a scope of the rating system. The corresponding scores are given by the IS rating tool to show which criteria weigh more and are dominant in improving project sustainability performance.

3. Research Approach

As discussed earlier, the research methodology begins by utilising the DPSIR (—driver-pressure-state-impact-response) framework to develop quantitative relationships among the selected indicators to ease the onerous task of system conceptualisation. Figure 1 illustrates the methodological approach of the research study. The development of the SD model includes a causal loop diagram (CLD), followed by a stock and flow model.

The primary purpose of the CLD is to depict the relationships between indicators and the direction of their influence on one other utilising DPSIR elements. The stock and flow model is built from the CLD by selecting appropriate scientific relationships through direct or indirect quantification of the model. The performances of indicators over the operation and maintenance phases derived from the stock and flow model are normalised via the entropy method, which is used to calculate the weight values of the indicators under the five index layers of the DPSIR. Finally, the SPI of different project options is analysed to determine the project's sustainability performance variation. The verification and validation of the model structure and the results were carried out before analysing the project's SPI for alternative options.

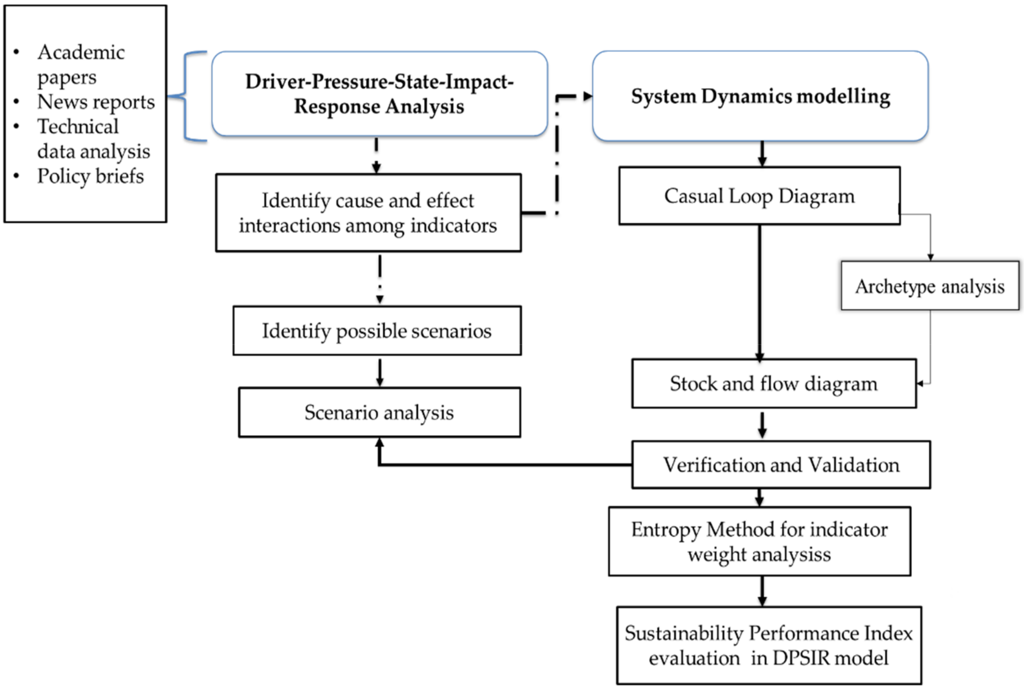


Figure 1. The methodological framework for integrating DPSIR with SD to analyse project SPI.

One of the main advantages of the framework is providing a theoretical explanation of how the problem emerged in the first place using the driving force element of the DPSIR framework. These driving forces can be entirely different for projects based on how the modeller defines the problem and boundaries set in the model variable selection process [25]. A further advantage of the methodology in Figure 1 is the utilising of 'archetypes' to describe dynamic phenomena and 'common stories' of CLDs that repeatedly occur in the system's diverse sets of behaviour and contexts [25,26].

This research identifies the corresponding sustainability criteria and indicators under each aspect, as shown in Table 1. In some cases, indicators designating an indistinguishable sustainability measure overlap, and therefore the names of the indicators, overlap in providing an indistinguishable sustainability measure. For example, jobs and employment tend to be related and have the same terminology and synonyms under the 'work' measure. Moreover, given the time constraints and availability of information, only the highly scored IS rating scheme's sustainability criteria from each aspect are chosen in this research study. The adapted definitions for the sustainability indicators and the factors influencing the performance of the selected indicators are provided in Tables 2 and 3, respectively. As shown in the following section, a case study analysis was conducted to demonstrate the research methodology and compare the sustainability performance of available alternative options.

Table 1. Selection of criteria and indicators under each aspect of sustainability.

No	Dimension	Criteria	ISCA Tool Awards Point	Indicators under Selected Criteria	References
1	Economic (E)	1.1. Business case 2.1. Benefits realisation	14.51 4.54	1.1.1. Financial net present value 1.1.2. Financial benefit-cost ratio 1.1.3. Economic net present value 1.1.4. Economic benefit-cost ratio	[27,28]
2	Environment (En)	2.1. Energy 2.2. Green infrastructure 2.3. Pollution 2.4. Material and resource recovery 2.5. Water 2.6. Ecology	9.27 3.54 1.45 5.99 6.54 4.54	2.1.1. GHG(CO_2-eq) emissions	[29–31]
3	Governance (G)	3.1. Innovation 3.2. Leadership 3.3. Sustainable procurement 3.4. Resilience 3.5. Culture and context	10 9.08 9.34 5.32 3.87	3.1.1. Innovation initiatives	[32]
4	Social (S)	4.1. Stakeholder engagement 4.2. Legacy 4.3. Heritage 4.4. Workforce	9.38 4.36 2.18 9.08	4.1.1. Congestion (volume-capacity ratio) 4.1.2. Road safety (accidents) 4.1.3. Employment (job) opportunities 4.1.4. Noise pollution	[30–35]

Table 2. A brief explanation of selected criteria and indicators for analysing road sustainability during the operation and maintenance phase.

Criteria	Explanation	Indicator	Explanation
Business case	This is a process of critically examining the opportunities, alternatives, project stages and economic and financial investment to recommend the best course of action to create business value [32].	Financial net present value (FNPV)	Measures the annual net financial benefit from the investor's perspective. Therefore, FNPV should be used when comparing mutually exclusive project options [27,28]. The option with the highest FNPV is the preferred option for an investor.
		Economic net present value (ENPV)	Measures a project's annual net economic benefit to society, including externalities in monetary terms [27,28].
		Financial benefit-cost ratio (FBCR)	This ratio provides a single measure that can support the decision to accept or reject a project in economic and financial terms. In a budget-constrained environment, the BCR can be used to rank and prioritise all projects in the budget pool [27].
		Economic benefit-cost ratio (EBCR)	

Table 2. *Cont.*

Criteria	Explanation	Indicator	Explanation
Stakeholder engagement	A crucial step that aims to involve or consider the needs of all project stakeholders in the planning, decision- making and implementation phases of a project. Satisfying stakeholder needs reduces the likelihood of conflict and sets clear project priorities by addressing the key issues relating to stakeholder viewpoints during project evaluation [31].	Congestion (volume-capacity ratio)	Volume-capacity ratio is one of the most important indexes to measure the congestion of a traffic network [27]. Key stakeholders concerned with congestion and hassle-free traffic include government and resident users [31].
		Road safety (crashes)	This measure includes accidents (crashes) leading to death and injury [33]. This indicator affects residential users (road users) are the primary stakeholder group affected by this indicator [31].
		Employment (job) opportunities	Measures the level of direct employment (people employed on the project) and indirect employment (people employed in the supply of goods or services to the project) [31].
		Noise emission	Measures unwanted sound and is officially reassessed whenever a new road is built, an existing road is altered, or traffic on the road increases [35]. High-impact stakeholders for this indicator include environmentalists.
Energy	The measure of consumption of traffic energy needs and maintenance/management needs [33,34].	Greenhouse gas (GHG(CO_2-eq)) emissions	Carbon dioxide equivalent (CO_2-eq) is a measure used to compare the emissions from various GHGs [34]. It allows different bundles of GHGs emitted from pavement materials and consumed fuel to be easily compared in a single measure (in terms of their total global warming impact). This is quoted as kg CO_2-eq per unit of energy consumed and emitted.
Innovation	Innovation advances the capabilities of road infrastructure and prompts the development of changes to accelerate results and lower risk [32].	Innovation initiatives	Measures the impacts of implementing innovation initiatives on road infrastructure; this study considers construction, technological, and financial structuring innovations [36].

Table 3. Factors influencing the sustainability indicators [5,8–11,27–33].

Sustainability Indicators	Influencing Factors	Sustainability Indicators	Influencing Factors
Financial net present value	Financial, operational and management cost	Innovation initiatives	Impact of initiatives on operational and maintenance cost
	Financial maintenance cost		Smart street lighting
	Investment cost (financial)		Supplementary cementitious material (SCM) replacement
	Per-period rate of discount		The unit cost of street lighting (CO_2-eq)
	Traffic volume		Unit cost of SCM (CO_2-eq)

Table 3. *Cont.*

Sustainability Indicators	Influencing Factors	Sustainability Indicators	Influencing Factors
	Maintenance activities interval	Congestion	Traffic volume
	Toll rate		Road capacity
	State government need/satisfaction		Traffic growth rate
Economic net present value	Economic maintenance cost		Road roughness
	Investment cost (economic)		Vehicular composition
	Per-period rate of discount		Price strategy for road toll
	Vehicle operating cost saving		Vehicular composition
	Vehicle travel time cost saving		Price strategy for road toll
	Accident cost saving		Road gradient
	Externalities cost		Road length
Financial benefit-cost ratio	Financial cash inflow	Road safety	Crash rate
	Financial cash outflow		Operating speed
	Discount factor		Resident (community) need/satisfaction
Economic benefit-cost ratio	Economic cash inflow	Employment opportunities	Direct job opportunities
	Economic cash outflow		Indirect job opportunities
	Discount factor		Operational and maintenance cost
Energy consumption	Fuel consumption		Resident (community) need/satisfaction
	Environmentalist (NGO) need/satisfaction	Noise pollution	Maintenance activities
	Vehicular composition		Noise mitigation measures
	Maintenance activities		Vehicular composition
	Pavement condition speed factor		Operating speed
	Road gradient		Resident (community) need/satisfaction
	Pavement condition speed factor		Environmentalist (NGO) need/satisfaction
	Road roughness		Resident (community) need/satisfaction

4. Case Study

The North-South Corridor link Northern Connector project in South Australia was selected as a case study as it is identified as one of Adelaide's most important transport corridors under the 30-year Strategic Plan for Greater Adelaide [37]. Infrastructure Australia has also identified the project's national significance and positive contribution to achieving Australia's policy goals. The corridor will cover a distance of 78 km between Gawler and Old Noarlunga and will form the primary route for north- and south-bound traffic, including freight vehicles. As it is a complex project, any change in project design can lead to changes in the scope, which represent the leading cause of cost overrun. In addition, as with any other road network, the accuracy level of traffic forecast for the Northern Connector project depends on many hidden factors, such as population growth rate, the applied traffic forecast models and road user attractiveness. The Northern Connector is a 15.5- km-long three-lane expressway proposed as part of the North-South Corridor (see Figure 2). The Australian Government has committed AUD 708 million to the project, with a contribution of AUD 177 million from the South Australian Government [38]. In the case study analysis, different impacts of project sustainability are destined to appear during the 30 years of its operational phase (i.e., from 2020 to 2050).

Figure 2. North-South Corridor project road map.

The main contribution of the Northern Connector project investment is to reduce the traffic capacity of the existing route from the Southern interchange to the Northern interchange. In addition, the implementation of the Northern Connector is expected to bring potential sustainability benefits, including reducing GHG(CO_2-eq) emissions, solving traffic congestion and improving safety for road users by reducing conflicts between vehicles at grade intersections, particularly from Port Wakefield Road [38]. Further, the operation of the Northern Connector also seeks to satisfy the needs of various stakeholders; for example, environmentalists are satisfied with GHG(CO_2-eq) emission savings due to the more favourable alignment, while road users are supportive as the distance travelled for most traffic will be reduced, and vehicles will not need to stop at junctions nor idle in congested traffic. Thus, the investment decision associated with the base case of implementing the Northern Connector project has achieved a consensus between key stakeholders. Based on this initial analysis, a rich picture is built in the next section to help the analyst explore this problematical situation and express it through a diagram that can show the relationships and interactions between key sustainability aspects of the project.

4.1. Sustainability Qualitative Analysis

4.1.1. Problem Identification and Scoping under the DPSIR Framework

The first step of conceptualisation in dynamic model development is deciding on the model purpose, which involves focusing on a problem and narrowing down the model before concretely stating the model purpose [39]. Developing a conceptual model generates multiple feedback loop mechanisms considering the interrelationships between indicators. This base case was constructed given a scenario of implementing a freeway and toll road option for the Northern Connector project. The DPSIR framework provides a high-level view of a causal framework for teasing out the crucial variables (indicators and their corresponding influencing factors) and provides a clear picture of their interplay. It also provides the starting point for hypothesising the qualitative relationships among the aspects of project sustainability. While drivers and pressures provide the basis for formulating scenarios, responses indicate the decision options to be analysed in the model. This study utilised the specific road infrastructure planning guidelines to identify qualitative 'black box' interrelationships among indicators and influencing factors [39,40].

Figure 3 briefly displays DPSIR as a high-level view to organise the linked system, starting with driving forces (road roughness, congestion, and travel time) and progressing to pressures (traffic volume, vehicle operating cost and vehicle travel time). Next, the impacts (noise emission, GHG(CO_2-eq) emissions, accidents) and state of road infrastructure (operating speed, toll income, employment opportunities, vehicle travel time saving, GHG saving, VOC saving) are assessed, leading to political responses (innovation initiative, price strategy and maintenance strategy). These steps act as a foundational input for the next steps of the SD—the CLDs [41].

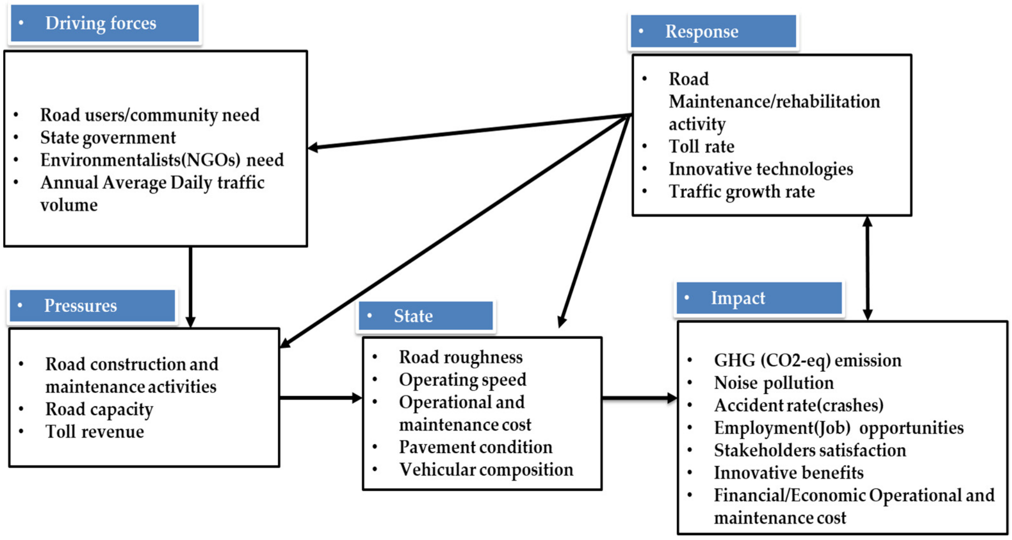


Figure 3. DPSIR framework through the problem scoping and structuring phase.

4.1.2. Identifying System Archetypes of Causal Loop Diagrams

A qualitative analysis is performed based on existing studies, varying goals and scopes, system boundaries and functional units of selected indicators and factors. For example, in Figure 4 the '+' signs at the arrowheads signify that the effect is positively related to the cause (an increase/decrease in variable 'A' leads to an increase/decrease in variable 'B'), while '−' signs signify the opposite [42]; 'R' indicates a reinforcing loop, 'B' indicates a balancing loop, and B1 stand for the loop number. It should be noted that there can be multiple reinforcing and balancing loops in a model, but the system boundary is based on the identified problem and the scope of the project.

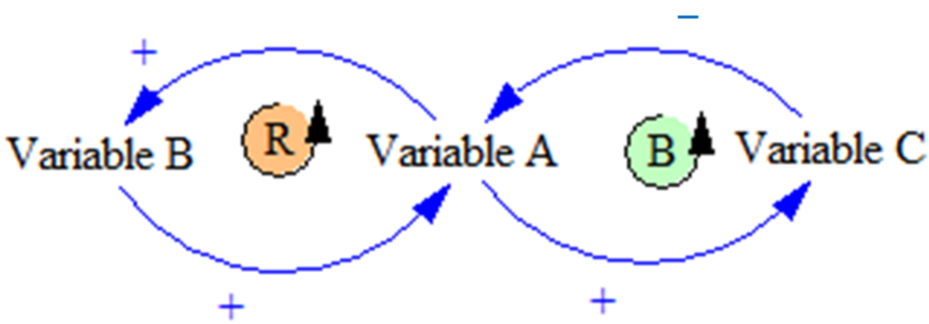


Figure 4. Relationships between variables in a CLD.

As the present study pertains to implementing the Northern Connector project and identifying its dynamic sustainability performance, problem identification begins by analysing the feedback mechanism for the driving forces of consideration and developing a new road (road roughness, travel time and congestion). The system archetypes are generated by considering how the indicators and influencing factors under other nodes/elements of the DPSIR framework affect the driving forces of sustainability. Therefore, this section utilises archetypes as lenses to analyse the feedback mechanism of the indicators under driving forces. We identified Success to Successful, Shifting the Burden and Limits to Success as useful archetypes for explaining the future project's sustainability problems.

i. Road roughness, road maintenance/rehabilitation activity and noise mitigation measures (Success to Successful archetype)

Under the Success to Successful archetype, two or more individuals, groups, projects, or initiatives vie for a limited pool of resources to achieve success [43]. This indicates that two reinforcing/balancing loops compete for a standard, limited resource. Figure 5 represents the CLD based on the Success to Successful archetype. The 'toll rate' acts as a shared resource for taking the edge off 'road roughness', affecting the 'operating speed' and 'noise emission'. Loops B1 and B2 are balancing loops stipulating a decrease in road roughness over time. Road surface roughness is an important parameter that indicates the comfort level of a ride over a road surface and is also related to safety, noise emission, operating speed, and vehicle operating cost [44–46]. Therefore, to elucidate the concept, both loops begin with the basic concept of an increase in road roughness during a 30-year operation and maintenance phase. The National Association of Australian State Road Authorities Roughness Meter (NAARSA in counts/km) is employed in this research to evaluate the roughness of the road.

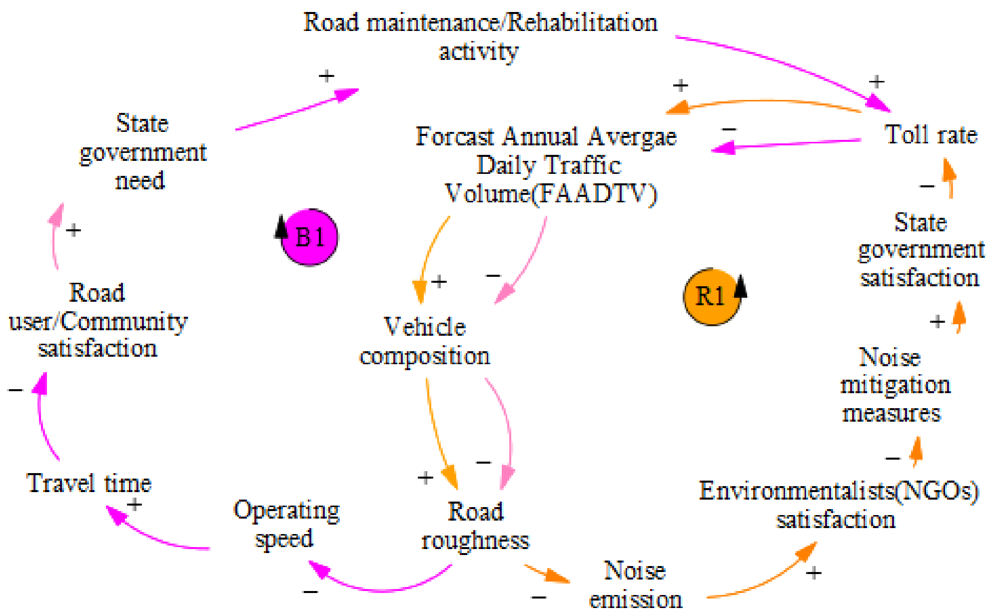


Figure 5. Success to Successful archetype.

Loop B1 begins with a decrease in operating speed due to road roughness. According to the empirical model proposed by Yu and Lu, a speed change of 0.85 km/h is observed for every 1 m/km increase in roughness [44]. As the speed of travelling decreases over time, the road network's travel time increases, leading to decreased road user satisfaction [45]. Thus, the Government undertakes specific maintenance or rehabilitation activities to improve the road pavement condition and improve the travel time. In general, an increase in a toll acts as a source of funding for road network maintenance works [47]. However, considering the dynamic nature of future uncertainties, an optimal road pricing strategy is challenging to implement in practice, and increasing a toll may cause uncertain traffic demand on the network [48]. Any decrease in traffic volume will eventually imply less impact on road roughness.

Loop R1 begins with the improved road roughness (pavement condition) from loop B1, which causes reduced noise emission per vehicle [49]. Eventually, this improves/satisfies environmentalists' requirements and strategies to undertake the noise mitigation measures. In general, road infrastructure costs may be divided into capital costs (typically up-front) and recurrent costs (maintenance and operating) [39]. Therefore, initiatives such as noise mitigation measures can affect maintenance costs (neutral, increase or decrease) depending on the initiative [49]. Thus, the Government tends to be neutral on toll charges as there is no additional need to undertake noise mitigation measures. However, according to the Senate Economic Reference Committee Report, a criticism is that tolls cause people to travel on alternative routes [47]. Thus, the traffic volume in the current situation may tend to increase in the long term, causing noticeable road surface deterioration.

ii. Congestion, GHG(CO_2-eq) emissions, fuel consumption and accidents (Shifting the Burden archetype)

In a Shifting the Burden situation, a problem symptom can be addressed by applying a symptomatic solution or a more fundamental solution [50]. When the symptomatic solution is implemented, the problem symptom is reduced or disappears, which lessens the pressure to implement a more fundamental solution. However, the symptom resurfaces over time, and another round of symptomatic solutions is implemented, causing a vicious reinforcing cycle. In addition, symptomatic solutions often produce side effects that further divert attention away from more fundamental solutions. The following driving force under consideration is congestion.

The background study under the formation of loop B2, as shown in Figure 6, begins with an increase in congestion, which causes an increase in road roughness. Further, keeping the road pavement/surface in good shape saves money and energy by reducing GHG(CO_2-eq) emissions [51]. In contrast, road maintenance and rehabilitation are also responsible for further GHG emissions from the contraflows of traffic and equipment in bringing deteriorated pavements to desirable quality standards [52]. Therefore, considering innovative technologies during road maintenance/rehabilitation activities can help to balance these emissions. However, most innovative materials and methods are cost-effective in economic rather than financial terms. For example, this research considers two innovative technologies/materials: (i) replacing cementitious concrete material with SCM in a 50% weight ratio and (ii) replacing LED lighting with solar-sourced lights. These two initiatives are drawn from the report A Review of the Emissions Reduction Opportunities, undertaken by the Department of Planning, Transport and Infrastructure (DPTI) of South Australia [40]. The report includes an assessment of emissions reductions achieved through sustainability initiatives implemented in Australia's range of infrastructure project types.

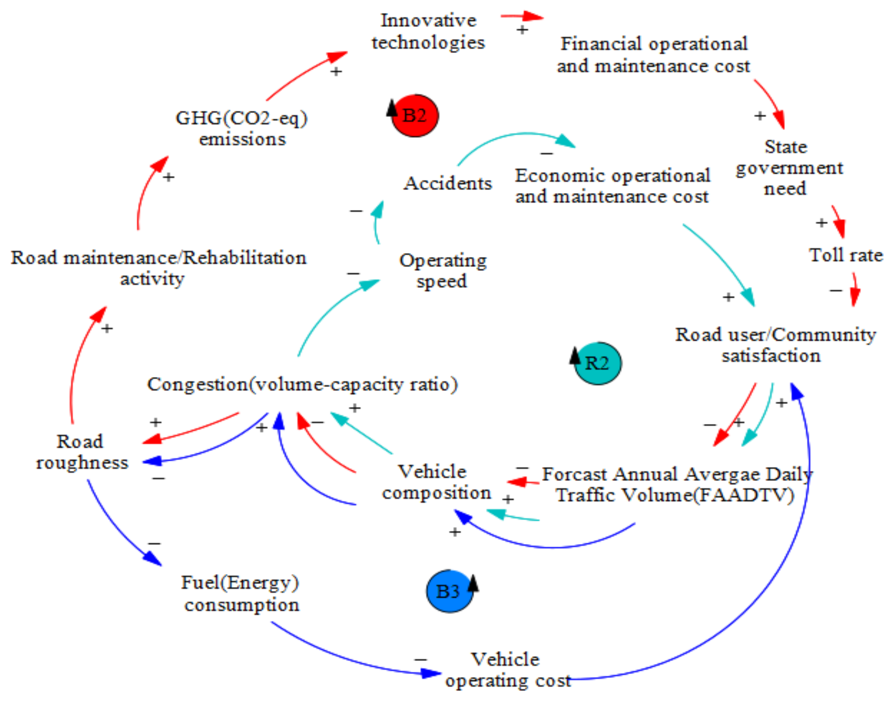


Figure 6. Shifting the Burden archetype.

In addition, the DPTI report suggests that considering expanded polystyrene walls as noise barriers contributes to minimising emissions, but the additional costs associated with implementing this initiative are high. Thus, this research suggests utilising 50% SCM replacement and solar street lighting under innovation initiatives for the selected road project. However, there is a considerable increase in the financial aspects of project operations and maintenance costs in order to implement these initiatives. Cost recovery for a particular service may be considered fair, and it may make sense to use a service to generate revenue because funds are always scarce. The report "Toll roads: Issues of building, financing and charging" from the Senate Economics Reference Committee of Australia also states that user charging can have various rationales [47]. Thus, increasing the toll rate to fund innovation initiatives can further cause a variation in travel demand that reduces congestion on the network and forms the balancing loop B2.

The balancing loop B3 begins with this reduced congestion resulting from loop B2, which means the pavement deteriorates at a slower pace. In 2006, a Missouri Department of Transportation (MoDOT) study reported a 2.461% increase in fuel efficiency on new smoother pavements relative to the rough pavement before resurfacing [52]. Additionally, BITRE 2017 released a report, 'Measuring infrastructure asset performance and customer satisfaction: a review of existing frameworks', stating that vehicle operating cost regarding fuel consumption plays a significant role in road user satisfaction, especially in private cars [53]. Therefore, vehicle operating costs affect the long-term traffic volume generated, thus increasing the traffic volume proportion and congestion, resulting in loop B3 being a balancing loop.

Loop R2 focuses mainly on the influence of increased congestion in loop B3 on traffic accidents, as these impose great economic and social costs on communities. Estimating the congestion—speed—crash relationship has long focused on roadway safety analysis [54,55]. Although there is an inverse relationship between accidents and congestion, it would imply a benefit of congested conditions for road safety. This poses a hypothetical situation for traffic management as both time and safety are significant factors related to increased user satisfaction [56]. Thus, loop R2 is a reinforcing loop with an increased traffic volume and increased congestion.

Overall, the fundamental solution to loop B2 under this archetype is to implement an innovation initiative to reduce GHG(CO_2-eq) emissions, but the toll rate implementation acts as a symptomatic solution that reduces the emissions long-term. Moreover, this symptomatic solution leads to sustainability benefits in terms of reducing fuel consumption and accident risk.

iii. Travel time, GHG(CO_2-eq) emissions, employment opportunities and congestion (Limits to Success archetype)

Under a Limits to Success archetype, growing actions initially lead to success, encouraging more of those efforts. Over time, however, the success itself causes the system to encounter limits, which slows down improvements in results. As success triggers the limiting action and performance declines, the tendency is to focus even more on the initial growing actions [43]. This paradox can help organisations avoid the Limits to Success trap.

The driving force 'travel time' is divisible as every minute of time savings is equally valuable. Loop B4 of Figure 7 begins with increased travel time as the road operational and maintenance phase elapses. As travel time increases congestion, fuel consumption also rises [57,58]. Thus, the carbon intensity of fuel further increases GHG(CO_2-eq) emissions. The proposal of specific policies by the Government to satisfy environmentalists can affect congestion and further reduce travel time on the network. For example, under the smart tolling system, a variable price may be charged for using the toll road at different travel times [47]. The innovative toll roading system sets a predetermined target for the desired travel time on a highway, making the road user pay for the route's extra travel time. This optimal system maximises the efficiency gains of a new road while minimising congestion issues and improving the travel time.

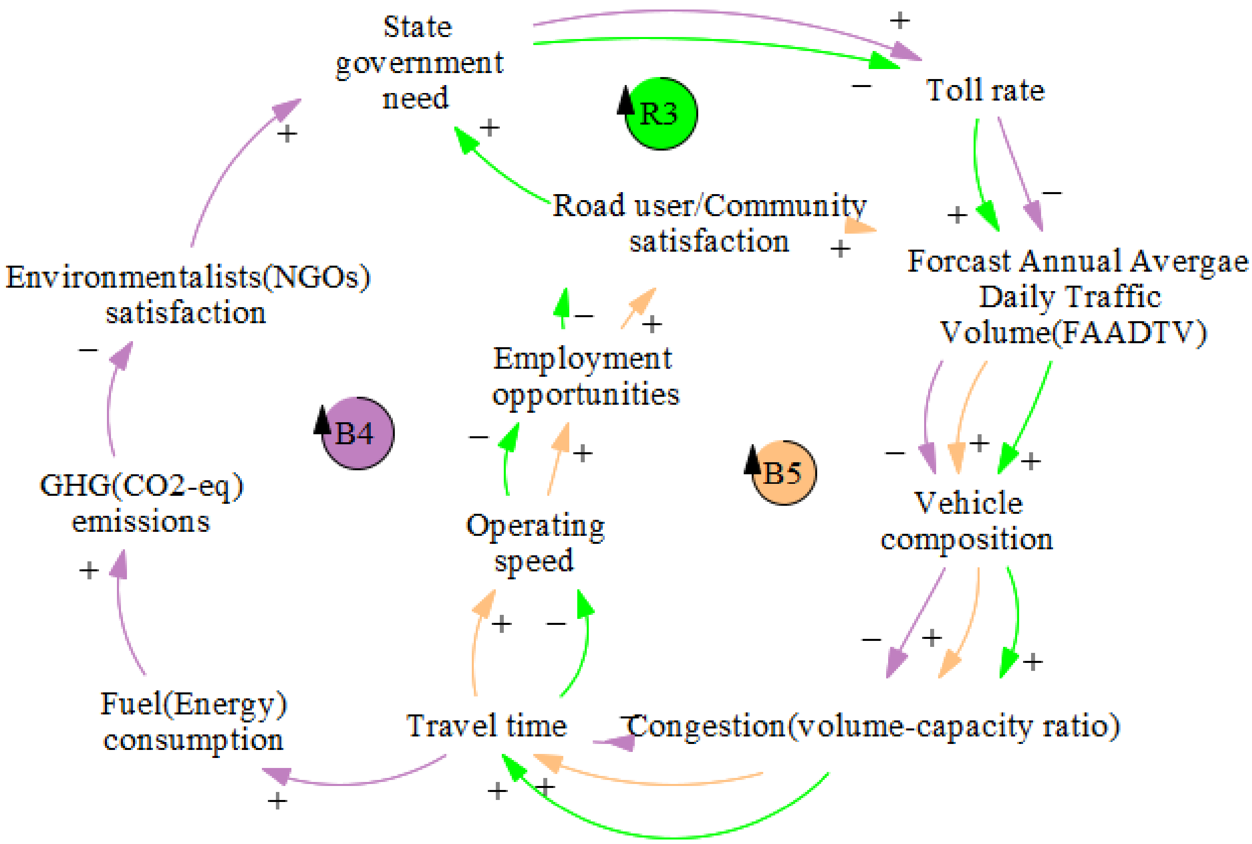


Figure 7. Limits to Success archetype.

It has long been acknowledged that road transport improves employment outcomes as it provides people with greater access to spatially dispersed job opportunities [58]. Therefore, the decreased travel time from loop B4 increases the road network's operating speed, making destinations more accessible and increasing employment opportunities [59]. Further, B5 acts as a balancing loop as an increase in road user satisfaction prompts future investment decisions surrounding the proximity of the road network. Indeed, this increases the number of trips generated under the traffic volume, leading to congestion during work hours, and thus increasing travel time.

The operating speed is 'the highest overall speed at which a driver can travel on a given highway under favourable weather conditions and prevailing traffic conditions' [60]. Thus, an increase in travel time from loop B5 indicates a decreased operating speed on the route. Further decreased feasible commute affects employment opportunities as road users with a low value of time switch to a less convenient mode or pay a charge that exceeds the value of their time savings. Thus, the tyranny of distance comes into play, implying that people must travel further and pay more operational costs to access employment and essential services [58]. Moreover, road users should only pay tolls when they cause congestion inside the toll ring. Therefore, toll discounting by the Government could increase the level of attraction of traffic volume towards the network, leading to an increased private vehicle proportion on a long-term basis. This induces congestion and increased travel time over the operational road phase, making R2 a reinforcing loop.

The next step is to utilise these loops to develop or inform some parts of the stock-flow quantitative model, covering the same set of relationships and other factors affecting the system.

4.2. Sustainability Quantitative Analysis

Once a good understanding of the problem situation is gained from the archetypes, model articulation begins by transforming the conceptual model to a quantitative representation to simulate the model. Consequently, formal modelling requires more precision than purely conceptual modelling. Formal modelling involves the identification of the stocks and flows [61]. It involves the specification of the functional forms representing the relationships between variables covering the same set of relationships. A stock collects all inflows and serves as the reservoir and source from which outflows emerge. A flow serves as a mode to deliver or drain resources from the stock. The value of a flow can be positive or negative. A positive flow is an inflow that fills the stock, and a negative flow is an outflow draining the stock. In Figure 8, the stock volume will change at different time points as both inflows and outflows are generated as time goes on.

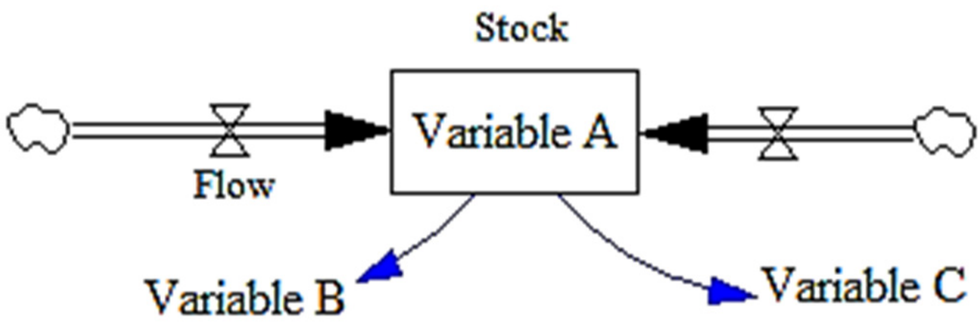


Figure 8. Stock and flow model of system dynamic model.

The relationship between the stock and the flow is established as follows [62]:

$$\text{Stock(t)} = \text{Stock (t} - \text{dt)} + \text{Flow(dt)} \quad (1)$$

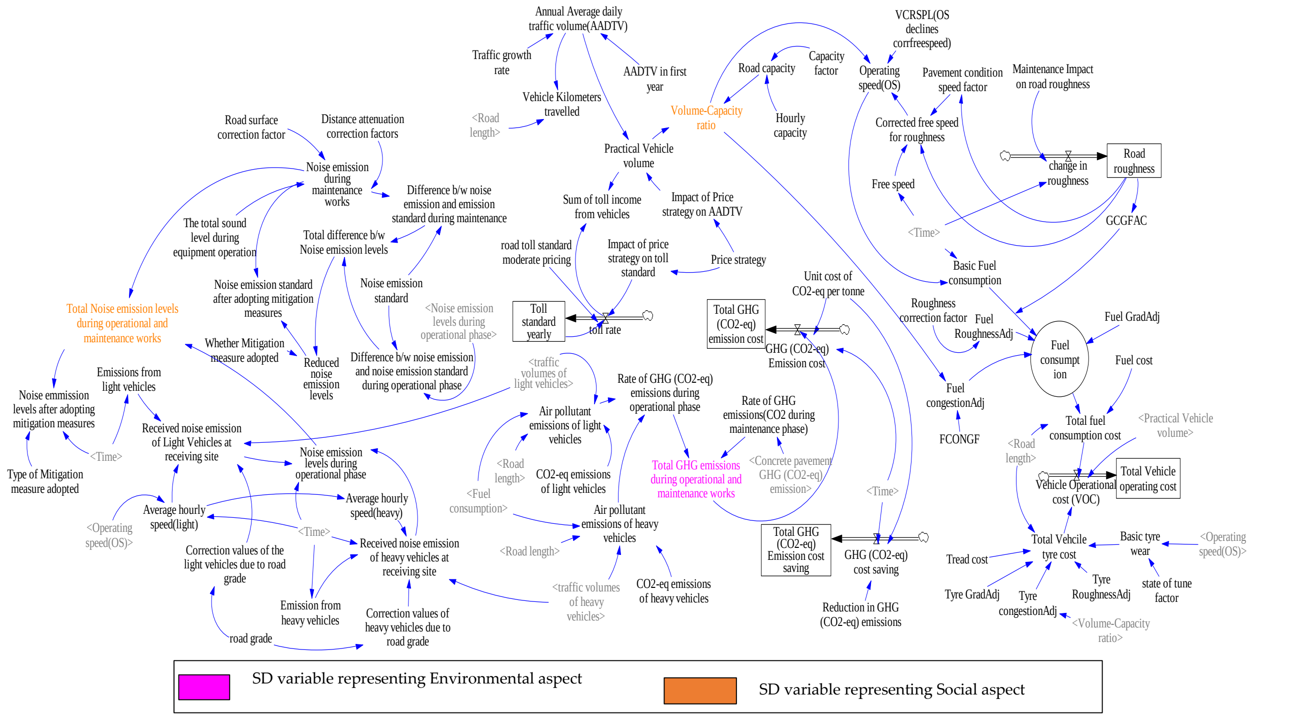
$$\text{Stock} = \int \text{Flow(dt)} \quad (2)$$

Multiple data sources were collected for use in the model parameterisation. Most of the information regarding indicators was derived from the project's cost-benefit analysis manuals and feasibility and technical study reports. The numerical values and initial conditions for indicators were based on data reports related to implementing sustainability initiatives in Australia [27,40]. Finally, quantitative relationships were developed using a desktop review from peer-reviewed scientific journal articles, government or government agency reports and web pages [37–40,63]. Figure 9a,b provide the sustainability indicators stock and flow model using the data collected.

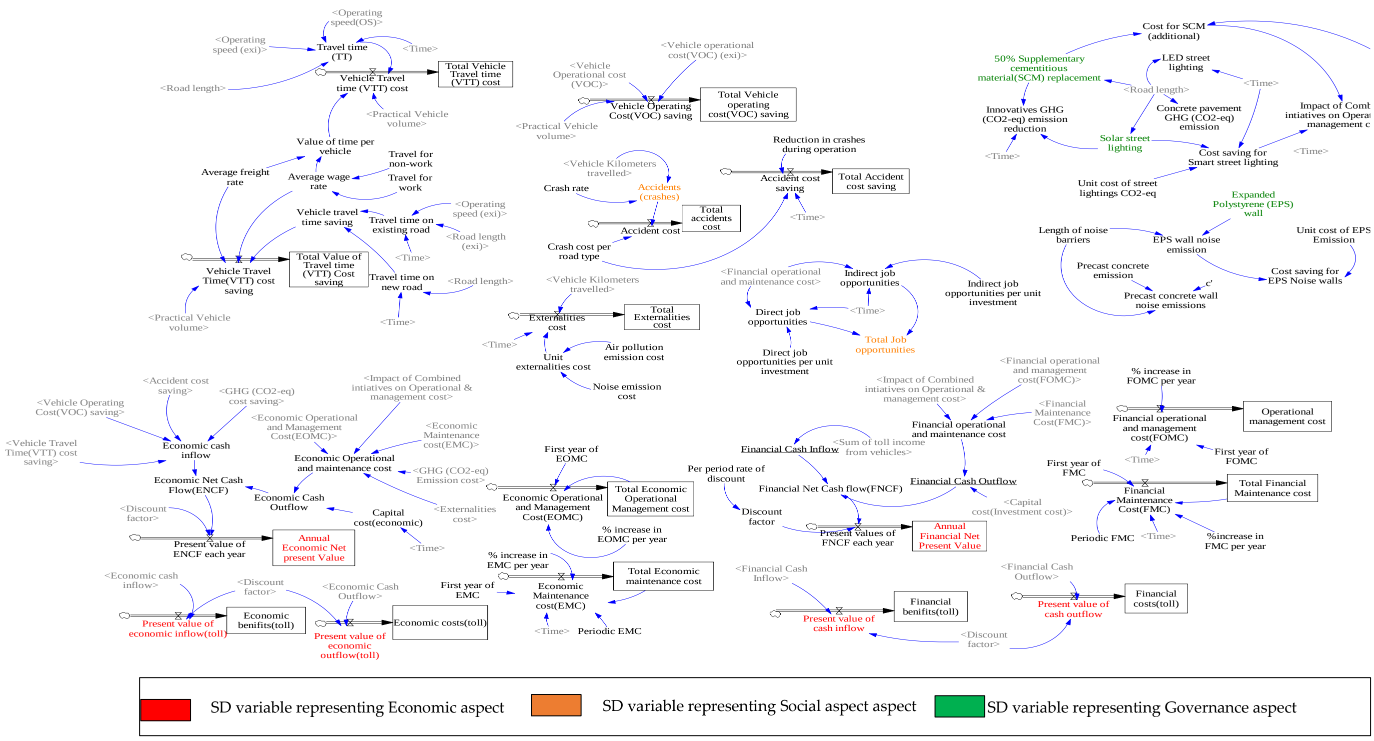
Appendix A (Table A1) provides essential variables, associated initial conditions and data values, while Appendix B provides detailed quantitative relationships utilised in the Vesnism® user interface of the developed model of the Northern Connector project. The next step is to explore what behaviour is affected by each variable over time using DPSIR elements and whether it is a valid representation of the actual project. Once built, many tests are available to build confidence in a model [64]. These tests help decision- makers to assess if the model is adequately constituted and a valid representation of the real-world system. Any uncertainties or errors in the test results imply that the modeller should re-check the quantitative relationships and data entries accordingly.

4.3. Findings and Discussion

The present study made efforts to evaluate the proposed sustainability indicator's performance over the 30-year operational phase. The base case was constructed to consider two options for the project case implementation: a freeway and a toll road.



(a)



(b)

Figure 9. (**a**) Stock and flow model of the road infrastructure system depicting environmental and social aspects; (**b**) Stock and flow model of the road infrastructure system depicting economic, governance and social aspects.

Notable points of discussion arising from the model results for the sustainability indicators include the following (see Figure 10):

- If the volume-capacity ratio representing 'congestion' reaches 1, the road operates at full capacity. In the proposed model, congestion is affected by demand uncertainty based on economic and environmental externalities caused by vehicular traffic. Therefore, the gradient of the congestion (volume-capacity ratio) graph in Figure 10 shows that the increase in road capacity is almost at a higher pace for the freeway.

- We can also observe the spikes in GHG(CO_2-eq) emissions at certain intervals during the operational and maintenance phase due to undertaking maintenance activities every five years. While traffic volume also contributes a considerable proportion to GHG emissions, this is higher for freeways than toll roads.
- It is clear from its mathematical relationship that noise emission is affected by operating speed, traffic volume and road gradient. The noise emission standard is 55 dB, but the freeway option exceeds noise emission standards by the end of the operational phase.
- On average, around 90 crashes are reduced during the operational and maintenance phase (30-year period) for the toll road option, mainly because of a decrease in congestion and better pavement conditions.
- According to the National Federation of Civil Contractors, seven workers are employed for every AUD 1 million invested in road infrastructure [65]. Apart from the investment cost, the difference in operation and maintenance cost between the freeway and the toll road is negligible, at only AUD 15 million.
- However, the cumulative increase in the maintenance cost for every five years increases by 1% considering the time value of money. Therefore, the difference in employment opportunities is close to 400 workers for toll and freeway roads in 30 years.
- The innovation initiatives indicator from the governance dimension has not been quantitatively evaluated as no data source is available for the innovative techniques/methods used in the Northern Connector project. Nevertheless, this indicator can be analysed under the innovation initiatives scenario.

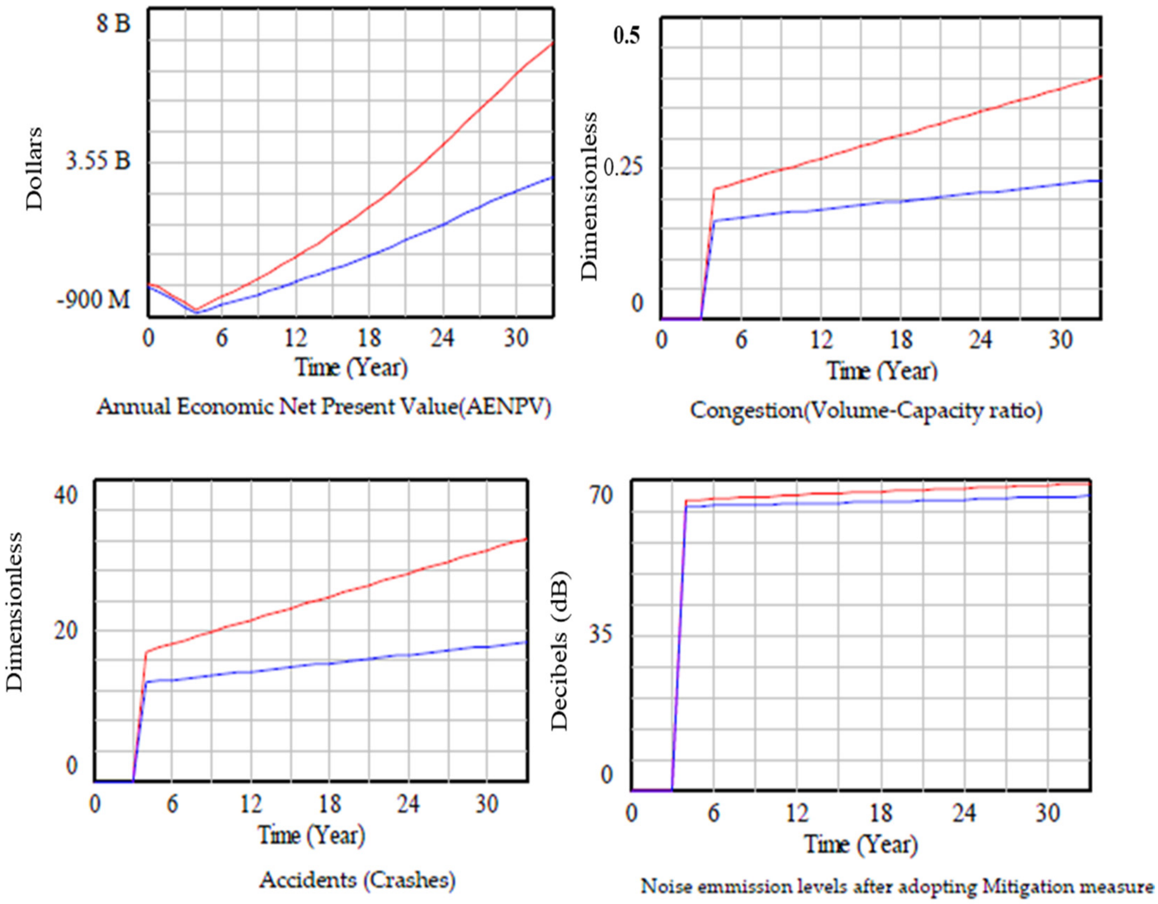


Figure 10. *Cont.*

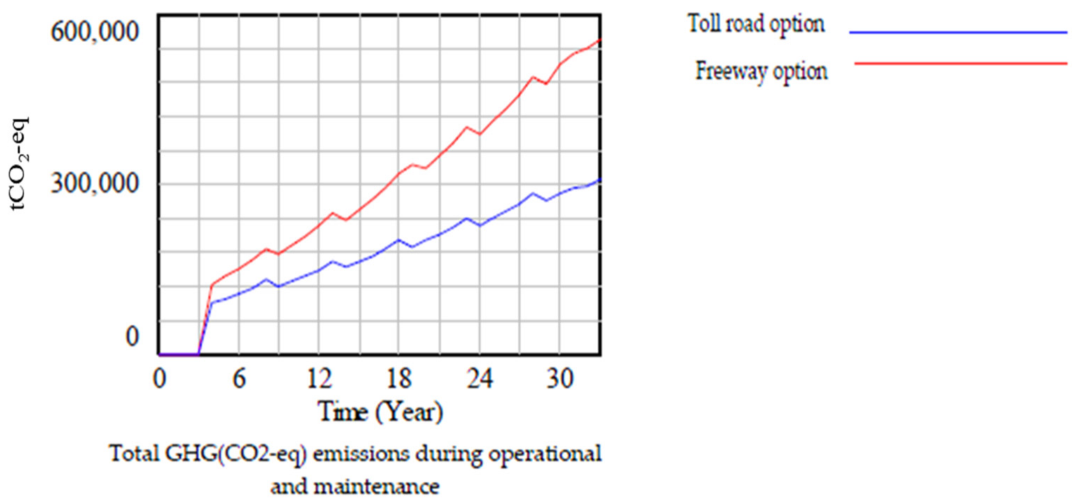


Figure 10. Indicators showing sustainability performance of the freeway and toll road options.

4.4. Model Validation: Building Confidence in the Model

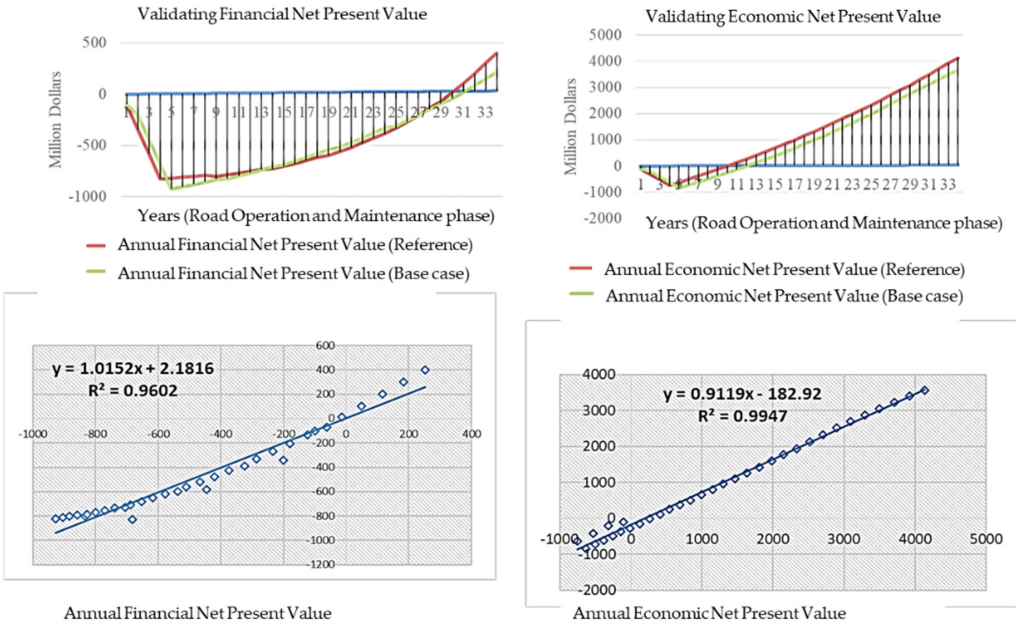
Validation is the next step to ensure that the model supports the objective truth. Before using the model for analysing the sustainability performance of policies, building confidence in the model structure and behaviour is essential. As no model exactly represents the real world, a model is verified and validated based on limitations and assumptions [66]. For example, instead of reflecting historical data, variables of the system should show meaningful relationships with others in the whole system. Therefore, the SD model in this research was built based on specific constraints and assumptions (Appendix A) to provide insights into the sustainability of road infrastructure projects and support policymakers in optimising investment options. This section presents tests to validate the developed SD model through 'behaviour replication' and 'robustness under extreme conditions' tests. Every equation must also be checked for 'dimensional consistency'.

4.4.1. Behavioural Replication Tests (Coefficient of Determination (R^2))

Building confidence in its structure and behaviour before analysing the model for evaluating sustainability performance and suggesting policies is essential. One critical test is the behaviour replication test, where the model's output behaviour is compared against historical data to ensure that the model satisfactorily reproduces the historical behaviour of the system. The results obtained for 30- years were compared with the project feasibility report data for model validation. It is evident through the R^2 value graph of Figure 11 that the percentage of the variance between data from the model and the project feasibility analysis report is highly acceptable.

4.4.2. Robustness under Extreme Conditions Tests of Key Variables

A robust model should have good performance even under extreme conditions; this supports enhanced reliability and confidence in using the model for policy and decision-making. To examine the reliability of the SD model, we tested the model to identify the indicators of performance if no project initiative had been undertaken on the route. These tests showed that the model behaved logically in response to changes in key variables. For example, in Figure 12, we can observe the GHG(CO_2-eq) emissions and congestion on the road for 30 years. If the Northern Connector project is not developed, the route will reach its maximum capacity by the end of the seventh year. Similarly, GHG emissions will increase rapidly, with 2 million tons of CO_2-eq emissions by the end of the 30-year period.



(**a**) (**b**)

Figure 11. (**a**) Validating the financial net present value of project when compared with reference utilising R-squared formula; (**b**) Validating the economic net present value of project when compared with reference utilising R-squared formula.

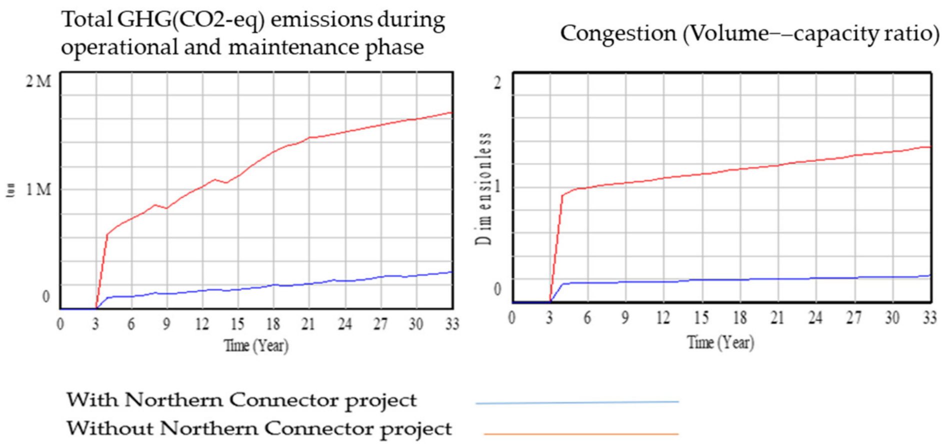


Figure 12. Robustness test of the indicator's congestion and GHG emissions.

4.4.3. Dimensional Consistency Test

The model must be dimensionally valid; it should be possible to convert the dimensions (or units of measure) of the variables on the right-hand side of the equation to the variable's dimensions on the left-hand side of the equation. This ensures that each equation in the model is checked for dimensional consistency. For example, considering the dimensions of the following equation used to calculate the stock 'annual economic net present value (AENPV):

$$\text{Annual economic net present value (AENPV) (t)} = \text{Annual economic net present value (AENPV)}' (t - dt) + (\text{present value of ENCF each year} \times c1) \times dt \quad (3)$$

where

c1 = dummy variable used to balance the dimensions of the model equation
ENCF = economic net cash flow

On the left-hand side of Equation (3), the dimension of the variable AENPV at the current time point (i.e., 't') is 'dollars'. On the other hand, the dimension of the right-hand side variables is 'dollars' for AENPV at the previous time point 't-dt', but the dimension for the flow variable 'present value of ENCF each year' is 'dollars/year' for the simulation time 'dt'. Hence, the dimensions of the variables on the right-hand side can be expressed as:

$$\text{Dollars} + (\text{Dollars/year}) \times \text{year}$$

By the ordinary laws of algebra, now 'year' can be deleted from the numerator and denominator of the second term. This equation can be modified to:

$$= \text{Dollars} \ + \ \text{Dollars}$$
$$= \text{Dollars}$$

Hence, the variable dimensions on the right-hand side of Equation (3) are unified to the variable's dimensions on the left-hand side, namely 'dollars'. All the dynamic evaluation model equations are checked and found to have dimensional consistency, as shown in Figure 13.

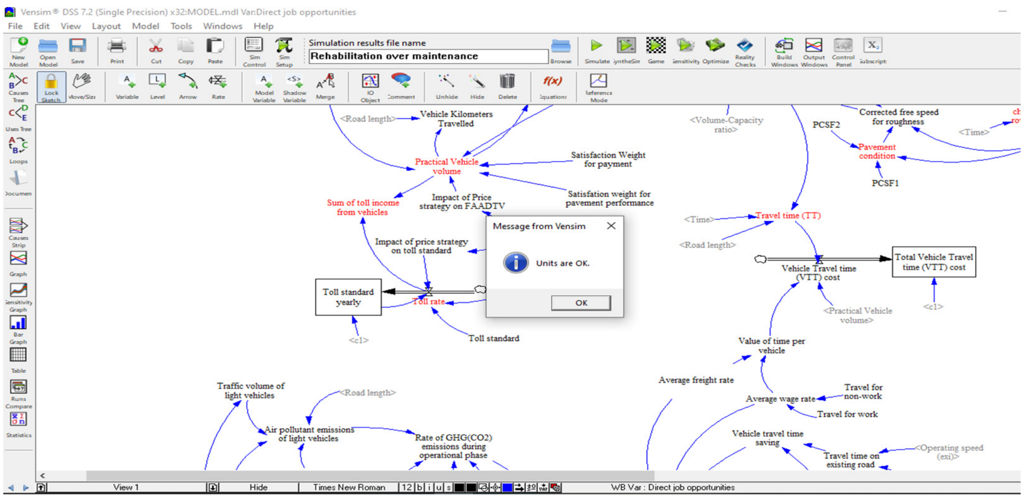


Figure 13. Vensim® model user interface representing dimensional consistency test.

4.5. *Sustainability Performance Index in the DPSIR Model*

This research article aims to develop a new systematic and comprehensive framework for evaluating a project's SPI value. As mentioned in Section 4.1.1, the model indicators are categorised under the DPSIR framework, and the index value of the indicators under drivers, pressures, state, impact and response are calculated, respectively. Determining the weights of these categorised indicators is essential for identifying their contribution to achieve sustainability objectives. The literature discusses two methods to determine an indicator's weight: subjective and objective weighting. Subjective weighting depends on group experts' research experience and advice, such as the analytic hierarchy process using the expert scoring method [29,67]. Objective weighting always uses mathematical calculations, such as the entropy weight method, principal component analysis and the coefficient of variation method.

The entropy weight method (EWM) is an important information weight model that has been extensively studied and practised [29]. Compared with various subjective weighting models, the most significant advantage of the EWM is the avoidance of the interference of human factors on the weight of indicators, thus enhancing the objectivity of the comprehensive evaluation results. Therefore, the EWM has been widely used in decision- making in recent years.

This article utilised the EWM to analyse sustainability indicators. The EWM evaluates value by measuring the degree of differentiation—the higher the degree of dispersion of the measured value, the higher the degree of differentiation of the index, and the more information that can be derived. Moreover, higher weight should be given to the index, and vice versa. According to the conventional literature, the results of the EWM are always reliable and effective [29].

4.5.1. Standardised Treatment of Evaluation Index

Due to the inconsistency of unit dimensions, the evaluation factors in the DPSIR model have no comparability; therefore, for evaluation research, the results from the SD model must be standardised to eliminate the influence of different units and measures among indicators. In this research, 'm' indicators and 'n' indexes are set in the evaluation, and the measured value of the *i*th indicator in the *j*th year is recorded as x_{ij}. The range of the entropy value E_i is [0, 1]. The greater the E_i differentiation degree of index i, the more information can be derived. Hence, a higher weight should be given to the index. The range standard method was used to evaluate for standardised treatment, and there are both positive and negative indicators in the model. The positive indicators are based on Equation (4); negative indicators are based on Equation (5) [29,68]:

$$K_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \tag{4}$$

$$K_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \tag{5}$$

To perform scaling and normalisation in the above equations, two values representing the variables' best (maximum) and worst (minimum) performance measures are defined. These two extreme values are not necessarily the theoretical maximum and minimum but represent reasonable scenarios for the selected performance measures [69]. For example, potential target/benchmark values can be used as maximum achievable values when developing scales. The study took these max-min values from the indicator performance measure of the existing road network when there was no development of the Northern Connector link.

The calculation formula of the weight of the indexes under the DPSIR framework is as follows.

The information entropy H_i of the ith evaluation index can be defined as:

$$H_i = -\frac{1}{\ln n} \sum_{j=1}^{n} f_{ij} \ln f_{ij} \tag{6}$$

Among these, i = 1, 2, . . . m; j = 1,2, ...n:

$$f_{ij} = \frac{K_{ij}}{\sum_{j=1}^{n} r_{ij}} \tag{7}$$

where $f_{ij} \leq 0$, $f_{ij} \ln f_{ij} = 0$, K_{ij} is the value after standardisation:

According to the information entropy of the evaluation index, the obtained information entropy H_i is substituted into Equation (8) to further determine the weight value of each evaluation index. The results of the weight of each indicator are shown in Table 4.

$$W_i = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i} \tag{8}$$

Table 4. Formulating the indexes for the DPSIR elements.

DPSIR Elements	Equation	Parameter Explanation
Driving Force Index (D)	$\sum_{i=1}^{n} W_{Di} \times K_{Di}$	K_{Di} is the quantised value of driving force index i, and W_{Di} is the weight of K_{Di}, i = 1,2,3 ... n
Pressure Index (P)	$\sum_{i=1}^{n} W_{Pi} \times K_{Pi}$	K_{Pi} is the quantised value of pressure index i, and W_{Pi} is the weight of K_{Pi}, i = 1,2,3 ... n
State Index (S)	$\sum_{i=1}^{n} W_{Si} \times K_{Si}$	K_{Si} is the quantised value of state index i, and W_{Ki} is the weight of K_{Si}, i = 1,2,3 ... n
Impact Index (I)	$\sum_{i=1}^{n} W_{Ii} \times K_{Ii}$	K_{Ii} is the quantised value of impact index i, and W_{Ii} is the weight of K_{Ii}, i = 1,2,3 ... n
Response Index (R)	$\sum_{i=1}^{n} W_{Ri} \times K_{Ri}$	K_{Ri} is the quantised value of response index i, and W_{Ri} is the weight of K_{Ri}, i = 1,2,3 ... n

4.5.2. The Construction of the Sustainability Performance Index

From the perspective of the DPSIR model, the driving force (D), pressure (P) and impact (I) are negatively correlated with road sustainability. To better evaluate the future plausible sustainability performance of the project, most of the state (S) indicators are positive. The response (R) indicators also positively contribute to improving sustainability performance. Based on the analysis of the above index layer relationship, the SPI model is established as follows [28]:

$$SPI = \frac{S \times R}{D \times P \times I} \tag{9}$$

The D, P, S, I and R indexes are developed using weighted summing for project alternatives (toll road and freeway). The distribution of project sustainability performance during the 30 years of the operation and maintenance phase can be obtained by conducting a definite integral of the function SPI. The higher the SPI, the more the project contributes to the attainment of sustainable development. A graphical representation of the change in SPI across the two alternative options is shown in Figure 14.

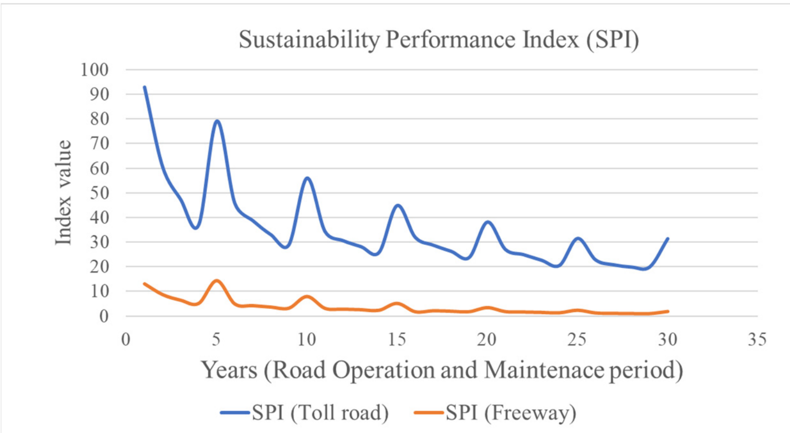


Figure 14. SPI of toll road and freeway options for the Northern Connector project.

5. Results and Discussion

Figure 14 indicates a decrease in the project's sustainability performance from 92.966 to 31.44 for the toll road option. This downward trend indicates the increased influence of driving forces and pressures towards sustainability irrespective of countermeasures in the form of responses (toll charges, maintenance activities) from the Government. The sustainability performance of the freeway option and its contribution towards sustainable development is very much lower from the beginning of its operational phase to the end, (i.e., a decline from 13.106 to 1.802). In addition, the downward trend in SPI can be divided into two stages—an increasing index value at every 5-year interval, followed by a further decrease until the next interval. This increase in the project's performance at regular intervals is mainly due to periodic maintenance works. The graph results also illustrate that the tolling system acts as a congestion pricing method to improve the average operating speed and help the Government with operational and maintenance costs. Therefore, choosing a tolling system is recommended to balance the sustainability aspects of the road project during its operation and maintenance phase. This also implies that the economics of managing the road positively affects other dimensions of sustainability. Moreover, optimising the toll rate or implementing a smart tolling system can further maximise the benefits of other sustainability aspects relative to the freeway option.

6. Conclusions and Recommendations

The developed methodology has several strengths. It combines several conceptual modelling methods (i.e., CLD, DPSIR, system archetypes, stock and flow diagrams) to help modellers identify and combine different data types and sources for model development. Future research is recommended in the following areas based on the limitations of the developed model. First, considering all the sustainability criteria and studying their dynamic nature could further strengthen the index value. Second, the methodology used in this research should be applied to different countries, thereby increasing the data available for future comparisons of the sustainability of infrastructure projects in different cultural contexts. Third, considering stakeholder engagement throughout the modelling process could help examine the utility of the employed methodology and produce artefacts to incorporate their perceptions and knowledge directly. Finally, scenarios can be a useful tool to support policy and guide action towards sustainability [70]. To do so, the potential sustainability impacts of different scenarios need to be assessed. Therefore, the future recommendation would be to consider specific policy scenarios that can be analysed under the scope of the model, some of which include varying toll charges, replacing rehabilitation work with periodic maintenance and introducing innovation initiatives. This would help decision- makers to identify policies (response strategies) that improve the overall sustainability performance of the project.

Author Contributions: S.K. performed the literature review, collecting, analysing the data, and writing (Qualitative and Quantitative analysis); Review of the writing and editing is performed by O.S. and A.R.; Supervision is carried out by S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: This research acknowledges three co-authors for their detailed comments and inputs.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. System dynamics model parameters.

Parameter	Initial Value	Unit	Source	Explanation
Capital cost (investment cost)	AUD 872 million	Dollars	[67]	AUD 708 million from the Australian Government and AUD 177 million from the South Australian Government
First year of FOMC	AUD 5.6 million	Dollars	[32]	Operation and management costs in first year

Table A1. *Cont.*

Parameter	Initial Value	Unit	Source	Explanation
Periodic FMC	AUD 28.7 million	Dollars	[67]	Periodic maintenance cost over 5-years
First year of FMC	AUD 5.7 million	Dollars	[32]	Financial maintenance cost in first year
Percentage increase in FOMC per year	0.01	Dimensionless	[68]	-
Capacity factor	0.1	Dimensionless	[29]	The capacity of road depends on model state roads (MSR)
Hourly capacity	12,000	Vehicles	[29]	Hourly capacity in PCE/hr by MRS for a three-lane road
Traffic growth rate	0.014	Dimensionless	[67]	Estimated traffic growth rate of 1.4% every year
Toll standard	5	Dollars/vehicles	[68]	Standard toll charges
Price strategy	5	Dimensionless	-	Depends on the toll pricing policy
Road length	15.6	km	[67]	-
SPVCR1	70	km/h	[29]	Operating speed at VCR of 1
PCSF1	0.96	Dimensionless	[29]	Pavement condition speed factor at 110 NRM
PCSF2	0.632	Dimensionless	[29]	Pavement condition speed factor at 250 NRM
VCRSPL (OS declines corrfreespeed)	0.3	Dimensionless	[29]	The VCR when operating speed declines from corrected free speed
Roughness correction factor	0.925	Dimensionless	[29]	Adjustment for fuel consumed
Fuel GradAdj	0.043	Dimensionless	[29]	Gradient adjustment factor
Fuel cost	1.36	Dollars/litre	-	Fuel cost during analysis
Tread cost	0.55	Dimensionless	[29]	Average tyre tread cost
Grad (VT)	0.02	Dimensionless	[29]	Tyre wear gradient adjustment
Rough (VT)	0.2	Dimensionless	[29]	Tyre wear roughness adjustment
Travel for non-work	17	Dollars/h/vehicles	[32]	Wage rate for non-working trip
Travel for work	43	Dollars/h/vehicles	[32]	Wage rate for working trip
CO_2-eq emissions of heavy vehicles	2.6	Tonne/litre/vehicles	[29]	-
CO_2-eq emissions of light vehicles	2.5	Tonne/litre/vehicles	[29]	-
Unit cost of CO_2 per tonne	23.5	Dollars/tonne	[32]	-
Crash rate	0.43	1/vehicles	[29]	Accidents per MVKT
Crash cost per road type	125,532	Dollars	[29]	Average accident cost based on crash rate
Per period rate of discount	0.03	Dimensionless	-	-
Noise emission standard	55	dB	[69]	Noise emission limit
Road surface correction factor	5	dB	[68]	Noise emission corrected for roughness
Distance attenuation correction factors	7	dB	[68]	Decrease in sound with distance from the sound source

Table A1. *Cont.*

Parameter	Initial Value	Unit	Source	Explanation
The total sound level during equipment operation	52	dB	[68]	Sound during maintenance activities
Emissions from light vehicles	48.6	dB	[68]	Average noise emission from light vehicles
Emission from heavy vehicles	68	dB	[68]	Average emission from heavy vehicles
Road grade	0.03	Dimensionless	[29]	Road steepness
Unit cost of SCM emissions	102	Dollars/tonne	[49]	Supplementary cementitious material cost
Unit cost of stree lightings CO_2-eq	4863	Dollars/tonne	[49]	
Indirect job opportunities per unit investment	5.11	Jobs/dollars/year	[66]	Indirect jobs per 1 million investments
Direct job opportunities per unit investment	1.79	Jobs/dollars/year	[66]	Direct jobs per 1 million investments
Annual average daily traffic volume (AADTV) in first year	25,683	Vehicles/day	[35]	Predicted traffic volume in first year of operational phase

Appendix B. Scripts and Model Equations

- Annual Average daily traffic volume (AADTV) = IF THEN ELSE (Time > 4, "Annual average daily traffic volume (AADTV) in first year"+ (Time-4) × "Annual average daily traffic volume (AADTV) in first year" × (1 + Traffic growth rate)−"Annual average daily traffic volume (AADTV) in first year"), IF THEN ELSE (Time = 4, "Annual average daily traffic −volume (AADTV) in first year"), IF THEN ELSE (Time = 4, "Annual average daily traffic volume (AADTV) in first year", 0))
- Road capacity = Hourly capacity/Capacity factor
- Free speed = IF THEN ELSE (Time ≥ 4, 110, 0)
- Vehicle Kilometres Travelled (VKT) = Road length × Practical Vehicle volume
- Volume-capacity Ratio (VCR) = (Practical Vehicle volume)/ (Road capacity)
- change in roughness = IF THE ELSE (Time = 8: OR: Time = 13: OR: Time = 18: OR: Time = 23: OR: Time = 28: OR: Time = 33, ((−Maintenance Impact on road roughness)), IF THEN ELSE (Time < 4, 0, 5))
- Traffic volumes of light vehicles = 0.75 × Practical Vehicle volume
- Traffic volumes of heavy vehicles = 0.25 × Practical Vehicle volume
- Basic Fuel consumption = IF THEN ELSE ("Operating Speed (OS)" ≥ 88: AND: "Operating Speed (OS)" ≤ 95: AND: Time ≥ 4, 0.1, IF THEN ELSE ("Operating Speed (OS)" > 95: AND: "Operating Speed (OS)" ≤ 110: AND: Time ≥ 4, 0.098, 0))
- Basic tyre wear = IF THEN ELSE (Time ≥ 4, 115.9, 0)
- Fuel RoughnessAdj = GCGFAC × Roughness correction factor
- Fuel congestionAdj = MIN (1, "Volume-capacity ratio" × FCONGF)
- Fuel consumption = IF THEN ELSE (Time ≥ 4, Basic Fuel consumption × (1 + Fuel congestionAdj + Fuel GradientAdj + Fuel RoughnessAdj), 0)
- Total fuel consumption cost = ((Fuel cost × Fuel consumption) × Road length)
- Operating Speed (OS) = IF THEN ELSE ("Volume–capacity Ratio (VCR)" < "VCRSPL (OS declines corrfreespeed)", Corrected free speed for roughness, IF THEN ELSE ("VCRSPL (OS declines corrfreespeed)" < "Volume–capacity Ratio (VCR)":AND:" Volume–capacity Ratio (VCR)" < 1, SPVCR1 + (Corrected free speed for roughness −SPVCR1) × ((1−"Volume–capacity Ratio (VCR)")/(1−"VCRSPL (OS declines cor-

rfreespeed)”)), IF THEN ELSE (1 < “Volume–capacity Ratio (VCR)”:AND: “Volume–capacity Ratio(VCR)” < 1.25, 30 + (SPVCR1−30) × ((1.25−”Volume–capacity Ratio (VCR)” “Volume–capacity Ratio (VCR)” < 1.25,30 + (SPVCR1−30) × ((1.25−“Volume–capacity Ratio (VCR)”)/(1.25−1)), 30)))

- Corrected free speed for roughness = IF THEN ELSE (Road roughness > 60, Pavement condition speed factor × Free speed, Free speed)
- Pavement condition speed factor = IF THEN ELSE (Road roughness ≤ 60, 1, IF THEN ELSE (Road roughness > 60: AND: Road roughness ≤ 110, 1−((1−PCSF1) × ((Road roughness−60)/(110−60))), MAX (PCSF1−((PCSF1−PCSF2) × ((Road roughness−110) /(250−110))), PCSF2)))
- Total Vehcile tyre cost = ((Basic tyre wear × (1 + ”CongestionAdj (VT)” + ”GradientAdj (VT)” + ”RoughnessAdj (VT)” + ”CurvatureAdj (VT)”) × Tread cost) × Road length)/1000
- Vehicle Operating cost (VOC) = (Total fuel consumption cost + Total vehicle tyre cost) × 365
- Travel time (TT) = IF THEN ELSE (Time ≥ 4, (Road length/“Operating Speed (OS)”), 0)
- Vehicle Travel time (VTT) cost = (365 × “Travel time (TT)” × Value of time per vehicle × Practical Vehicle volume)
- Value of time per vehicle = 0.7 × Average wage rate + 0.3 × Average freight rate
- Average hourly speed (heavy vehicles) = “Average hourly speed (light vehicles)“ × 0.8
- Average hourly speed (light vehicles) = IF THEN ELSE (Time ≥ 4, 212 × ((traffic volumes of light vehicles)ˆ(−0.175)) × (“Operating Speed (OS)”/120), 0)
- Average wage rate = Travel for work + Travel for non-work
- Accidents (crashes) = (Crash rate × “Vehicle Kilometres Travelled (VKT)”)/10,000
- Accidents cost = “Accidents (crashes)” × Crash cost per road type
- Unit externalities cost = (Air pollution externality cost + Noise emission externality cost)
- Externalities cost= IF THEN ELSE (Time ≥ 4, Unit externalities cost ×” Vehicle Kilometres Travelled (VKT)” × 365,0)
- Air pollutant emissions of heavy vehicles = (“CO_2-eq emissions of heavy vehicles” × Traffic volume of heavy vehicles × Road length × Fuel consumption)
- Air pollutant emissions of light vehicles = (“CO_2-eq emissions of light vehicles” × Fuel consumption × Road length × Traffic volume of light vehicles)
- “Rate of GHG(CO_2-eq) emissions during operational phase” = IF THEN ELSE (Time ≥ 4, (Air pollutant emissions of heavy vehicles + Air pollutant emissions of light vehicles), 0)
- “Rate of GHG(CO_2-eq) emissions during operational phase” = IF THEN ELSE (Time = 5: OR: Time = 10: OR: Time = 15: OR: Time = 20: OR: Time = 25: OR: Time = 30, (−0.35 × Percentage Quantity of Asphalt Binder replacement + 0.92 × Percentage Quantity of Recycled Asphalt pavement) × Road length × GHG emissions of concrete pavement × 13, 0)
- Total GHG(CO_2-eq) emissions during operation and maintenance work = “Rate of GHG(CO_2-eq) emissions during operational phase” + “Innovatives GHG(CO_2-eq) emission”
- GHG emissions cost = ((“Unit cost of CO_2-eq per tonne” + (Time)) ×” Total GHG(CO_2-eq) emissions during operational and maintenance”) × 10
- GHG(CO_2-eq) emissions cost saving = IF THEN ELSE (Time ≥ 4, (“Unit cost of CO_2-eq per tonne” + Time × c9 × c1) × (“Reduction in GHG(CO_2-eq) emissions (Base case)”), 0)
- Noise emission levels during operational phase = 10 × LOG (10ˆ(0.1 × Received noise emission of light Vehicles at receiving site) + 10ˆ(0.1 × Received noise emission of heavy vehicles at receiving site), 10)
- Received noise emission of Light Vehicles at receiving site = (Emissions from light vehicles + 10 × LOG ((traffic volumes of light vehicles/(Operating speed)), 10) +Correction values of the light vehicles due to road grade−13)

- Received noise emission of heavy vehicles at receiving site = (Emission from heavy vehicles + 10 × LOG ((traffic volumes of heavy vehicles/(Operating speed)), 10) + Correction values of heavy vehicles due to road grade−13)
- Difference bw Noise emission and emission standard during maintenance = IF THE ELSE (Time = 8: OR: Time = 13: OR: Time = 18: OR: Time = 23: OR: Time = 28: OR: Time = 33, Noise emission during maintenance – Noise emission standard, 0)
- Difference bw Noise emission and Noise emission standard during Operational phase = Noise emission levels during operational phase − Noise emission standard
- Emissions from light vehicles = 62.6 + 0.32 × Operating speed
- Emission from heavy vehicles = 77.2 + 0.82 × Operating speed
- Noise emission during maintenance = IF THEN ELSE (Time = 8: OR: Time = 13: OR: Time = 18: OR: Time = 23: OR: Time = 28: OR: Time = 33, (The total sound level during equipment operation −Distance attenuation correction factors + Road surface correction factor), 0)
- Noise emission levels during operational phase = IF THEN ELSE (Time ≥ 4, 10 × LOG (10^(0.1 × Received noise emission of Light Vehicles at receiving site) + 10^(0.1 × Received noise emission of heavy vehicles at receiving site), 10), 0)
- Noise emission standard = 63
- Noise emission standard after adopting Mitigation measure = IF THEN ELSE (Reduced noise emission levels = 1: OR: Reduced noise emission levels = 0, Noise emission during maintenance, IF THEN ELSE (Reduced noise emission levels = 2, Noise emission during maintenance−5, IF THEN ELSE (Reduced noise emission levels = 3, Noise emission during maintenance −10, IF THEN ELSE (Reduced noise emission levels = 4, Noise emission during maintenance−15, IF THEN ELSE (Reduced noise emission levels =5, Noise emission during maintenance−20, Noise emission during maintenance−25)))))
- Noise emission levels after adopting Mitigation measure = IF THEN ELSE (Type of Mitigation measure adopted = 1: OR: Type of Mitigation measure adopted, IF THEN ELSE (Type of Mitigation measure adopted = 2, Total Noise emission levels during operation and maintenance works−5, IF THEN ELSE (Type of Mitigation measure adopted = 3: AND: Time ≥ 4, Total Noise emission levels during operation and maintenance work−10, IF THEN ELSE (Type of Mitigation measure adopted = 4, Total Noise emission levels during operation and maintenance works−20, 0))))
- Correction values of heavy vehicles due to road grade = 98 × road grade
- Correction values of the light vehicles due to road grade = 73 × road grade
- Total Noise emission levels during operational and maintenance works = IF THEN ELSE (Time = 8: OR: Time = 13: OR: Time = 18: OR: Time = 23: OR: Time = 28: OR: Time = 33, 10 × LOG(10^(0.1 × Noise emission levels during operational phase) + 10^(0.1 × Noise emission during maintenance), 10), Noise emission levels during operational phase)
- 50% Supplementary cementitious material (SCM) replacement = (423 × 6 × 0.6 × Road length)/30
- Cost for SCM (additional) = Unit cost of SCM emissions × 0.6 × 6 × ”50% Supplementary cementitious material (SCM) replacement”
- Cost saving for Smart street lighting = IF THEN ELSE (Time ≥ 4, Unit cost of street lightings × 0.6 × Solar street lighting
- Economic Benefits (toll) = INTEG (“Present value of economic inflow (toll)”, 0)
- Economic cash inflow = Accidents cost saving + “GHG(CO_2-eq) emissions cost saving” + “Vehicle Operating Cost (VOC) saving” + ”Vehicle Travel Time (VTT) cost saving”
- Economic Cash Outflow = Economic Operational and maintenance cost + ”Capital cost (economic)”
- Economic Costs (toll) = INTEG (“Present value of economic outflow (toll)”, 0)
- Economic Maintenance cost (EMC) =IF THEN ELSE (Time = 8: OR: Time = 13: OR: Time = 18: OR: Time = 28: OR: Time = 33, Periodic EMC, IF THEN ELSE (Time < 4,

0,IF THEN ELSE (Time = 23, 2 × Periodic EMC, (percentage increase in EMC × Total Economic maintenance cost) + First year of EMC)))

- Economic Net Cash Flow (ENCF) = Economic cash inflow-Economic Cash Outflow
- Economic Operational and maintenance cost = "Economic Operational and Management Cost (EOMC)" + "Economic Maintenance cost (EMC)" + "GHG emissions cost + Externalities cost" + "Impact of Combined initiatives on Operational & management cost"
- Economic Operational and Management Cost (EOMC) = IF THEN ELSE (Time = 4, First year of EOMC, IF THEN ELSE (Time < 4, 0, (percentage increase in EOMC × Total Economic Operational Management cost + First year of EOMC)))
- Financial Benifits (toll) = INTEG (Present value of cash inflow, 0)
- Financial Cash Inflow = Sum of toll income from vehicles
- Financial Cash Outflow = Financial operational and maintenance cost + "Capital cost (Investment cost)"
- Economic cash inflow = Accidents cost saving + "GHG(CO_2-eq) emissions cost saving" + "Vehicle Operating Cost (VOC) saving" + "Vehicle Travel Time (VTT) cost saving"
- Economic Cash Outflow = Economic Operational and maintenance cost + "Capital cost (economic)"
- Financial Costs (toll) = INTEG (Present value of cash outflow, 0)
- Financial Maintenance Cost (FMC) = IF THEN ELSE (Time = 8: OR: Time = 13: OR: Time = 18: OR: Time = 23: OR: Time = 28: OR: Time = 33, Periodic FMC, IF THEN ELSE (Time < 4, 0, (percentage increase in FMC × Total Financial Maintenance cost) + First year of FMC))
- Financial Net Cash flow (FNCF) = Financial Cash Inflow − Financial Cash Outflow
- Financial operational and maintenance cost = "Financial Operational and Management Cost (FOMC)" + "Financial Maintenance Cost (FMC)" + Impact of Combined initiatives on Operational and management cost
- Financial Operational and Management Cost (FOMC) = IF THEN ELSE (Time = 4, First year of FOMC, IF THEN ELSE (Time > 4, ((percentage increase in FOMC × Total Operational management cost + First year of FOMC)), 0))
- Impact of management strategy on F = WITH LOOKUP (WITH LOOKUP (Management strategy, ([(0,0)–(10,10)], (1,0.8), (2,0.65), (3,0.6), (4,0.55), (5,0.5)))
- Impact of Price strategy on F = WITH LOOKUP (WITH LOOKUP (Price strategy, ([(0,0)–(10,10)], (1,1.983), (2,1.484), (3,1), (4,0.8), (5,0.76), (6,0.65), (7,0.6)))
- Impact of price strategy on toll standard = WITH LOOKUP (Price strategy, ([(0,0)–(10,10)], (1,0.01), (2,0.02), (3,0.03), (4,0.04), (5,0.05), (6,0.06), (7,0.07)))
- Impact on mitigation measures on operational and maintenance cost= WITH LOOKUP (Type of Mitigation measure adopted, ([(0,0)–(10,10)], (0,0), (1,0), (2,0.001), (3,0.002), (4,0.0035), (5,0.005), (6,0.007)))
- Indirect job opportunities = IF THEN ELSE (Time ≥ 4, Indirect job opportunities per unit investment × Financial operational and maintenance cost, 0)
- Financial Management strategy = IF THEN ELSE (Road roughness 60: AND: Road roughness ≤ 80, 1, IF THEN ELSE (Road roughness ≥ 80: AND: Road roughness ≤ 100, 2, IF THEN ELSE (Road roughness ≥ 100: AND: Road roughness ≤ 120, 3, IF THEN ELSE (Road roughness ≥ 120: AND: Road roughness ≤ 140, 4, 5))))
- Operational and maintenance cost = Routine Maintenance cost + Operational management cost
- Present value of cash inflow = Discount factor × Financial Cash Inflow
- Present value of cash outflow = Financial Cash Outflow × Discount factor
- Present value of ENCF each year = (Discount factor × "Economic Net Cash Flow (ENCF)")
- Present values of FNCF each year = (Discount factor × "Financial Net Cash flow (FNCF)")
- Present values of FNCF each year = Discount factor × Financial Net Cash flow
- Discount factor = 1/(1 + Per period rate of discount)^(Time−1)

- Rate of change of OMC next year = IF THEN ELSE (Time = 1, First year of OMC, "% increase in OMC per year "× Operational management cost)
- Rate of change of RMC 5 year = IF THE ELSE (Time = 5: AND: Time = 10: AND: Time = 15: AND: Time = 20: AND: Time = 25: AND: Time = 30, Routine MC per 5 year, 0)
- Financial benefit-cost ratio = Financial Net Cash flow/("Capital cost (Investment cost)" + Operational and maintenance cost)
- Emission reduction = (Unit cost of CO_2 per tonne + Time) × GHG emissions reduction operational phase
- Sum of toll income from vehicles = Practical Vehicle volume × Toll standard each day
- Toll standard each day = road toll standard moderate pricing × Impact of price strategy on toll standard
- Practical vehicle volume = Annual Average daily traffic volume (AADTV) × Impact of Price strategy on FAADTV
- Impact of price strategy on toll standard = With LOOKUP (Price strategy on road toll, ([(0,0)–(10,10)], (1,1), (2,1.5), (3,3), (4,5), (5,6))
- Impact of Price strategy on FAADTV = With LOOKUP (Price strategy on road toll, ([(0,0)–(10,10)], (1,1.983), (2,1.484), (3,1), (4,0.8), (5,0.69))
- Total Job opportunities = Indirect job opportunities + Direct job opportunities
- Direct Employment opportunities = Operational and maintenance cost × Direct job opportunities per unit investment
- Indirect Employment opportunities = Capital cost (Investment cost) × Indirect job opportunities per unit investment
- Economic OC per year=IF THEN ELSE (Time = 1, First year of OC, "% increase in OC per year "× Economic Operational Management cost)
- Ecoomic MC per year = IF THEN ELSE (Time = 5: AND: Time = 10: AND: Time = 15: AND: Time = 20: AND: Time = 25: AND: Time = 30, Economic maintenance cost per 5 year, 0)
- Economic benefit–cost ratio = Economic Net Cash Flow/(Economic Operational and maintenance cost + Economic investment cost)
- "Impact of Combined initiatives on Operational & management cost" = "Cost for SCM (additional) "+ Cost saving for Smart street lighting
- "Concrete pavement (GHG emission)" = 1821 × 6 × 0.6 × Road length × c2
- "50% Supplementary cementitious material (SCM) replacement = (423 × 6 × 0.6 × Road length × c2)/30
- Innovative GHG emission reduction = IF THEN ELSE (Time ≥ 4, Solar street lighting + "50% Supplementary cementitious material (SCM) replacement", 0)
- Solar street lighting = (492 × 0.6 × Road length × c2)/30
- LED street lighting = IF THEN ELSE (Time ≥ 4, 0.6 × 492 × Road length × c2, 0)
- Cost saving for Smart street lighting = IF THEN ELSE (Time ≥ 4, "Unit cost of street lightings CO_2-eq" × 0.6 × Solar street lighting, 0)
- "Cost for SCM (additional)" = Unit cost of SCM emissions × 0.6 × 6 × "50% Supplementary cementitious material (SCM) replacement"

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