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Mitigating the Traffic Congestion in the Urban Area Using the Integration of System Dynamics and Genetic Algorithm Approaches

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Abstract Urban traffic congestion has worsened in many countries today. This problem is getting worse for most urban areas globally, including Kuala Lumpur, Malaysia's capital city. It is predicted that the demand for mobility will increase tremendously as the city grows at a faster rate in terms of population, infrastructure, and economic activities in the next ten years. This paper aims to develop an integration of system dynamics (SD) with genetic algorithm (GA) approaches known as SD-GA model aiming to optimise the congestion index and mode share of transportation values in the year 2030 in Malaysia. The developed SD-GA model results show that the best level of congestion index is 0.41367 while the percentage of mode share is 78.41% in 2030. From all the tested travel demand variables, bus fare subsidies and bus route expansion rate emerged as the two highest increment percentages in achieving the best minimal value of mode share and congestion index. From the managerial perspective, this research contributes to the transportation industry by suggesting strategies to mitigate the high congestion index and optimise mode share in Kuala Lumpur.

Keywords Congestion Index, Mode Share, Public Transportation, SD-GA Model, Genetic Algorithm, System Dynamics

1. Introduction

As Malaysia's economy grows, Kuala Lumpur has become one of the world's fastest-growing cities. Kuala Lumpur including the Federal Territory of Kuala Lumpur, Selangor district of Petaling, Klang, Gombak, and Hulu Langat covers an area of 1084 km^2 [1]. The city of Kuala Lumpur is currently inhabited by a population of approximately 6.197 million people in 2009 and this is expected to grow up to 10 million by 2020 [2]. The economic growth in Kuala Lumpur has contributed to the increase in household income of its residents which prompted to the high number of car ownership. Ministry of Transport Malaysia (2020) reported that 6,521,419 of motorcar was registered in the year 2020 compared to 2019, which was 6,444,245 registered motorcars [3]. This further increases transportation use, which is necessary for economic growth because it requires a steady flow of people and products to move. As a result, the number of vehicles on the road in Kuala Lumpur has reached almost thirteen million, constituting almost 90 percent of the private vehicles' trips per day in 2017 [4]. This phenomenon creates severe traffic congestion in the city.

Traffic congestion is defined as the travel demand exceeding the traffic supply of the existing roadway facilities [5,6]. Besides, traffic congestion can be defined as the incremental delay due to interactions among commuters on the roadway, particularly when the traffic reached the traffic capacity that creates congestion index [7]. The congestion index is the ratio of the number of vehicles on the road divided by the weight of vehicle capacity on the road [7,8]. The bigger the ratio of the congestion index as it approaches 1.00, the more congested the road condition would be [7,9].

It is known that severe traffic congestion contributes to the switching trend of mode share. Mode share is the percentage of trips made by travellers to commute to their destination by transportation mode [10]. Figure 1 shows the mode share trend of private and public transportations in Kuala Lumpur from 1970 to 2012. The figure presented that the mode share of public transportation in Kuala Lumpur has fallen from 47 percent in the 1970s to 19 percent in 2012. In contrast, the mode share of private transportation has risen from 53 percent in the 1970s to 81 percent in 2012 [10]. The switching trend of public transportation to private vehicles is due to poor integration and lack of service quality [11,12].

In fact, Malaysia has a comparatively low mode share of public transportation during the same year compared to other international cities such as Hong Kong with 90 percent, Singapore with 63 percent and London with 55 percent [13]. Unlike other developed countries such as Japan as a model, the distributions of share trips between public transportation and private transportation are approximately in a ratio of 70:30, allowing them to have a more sustainable transportation system [14].

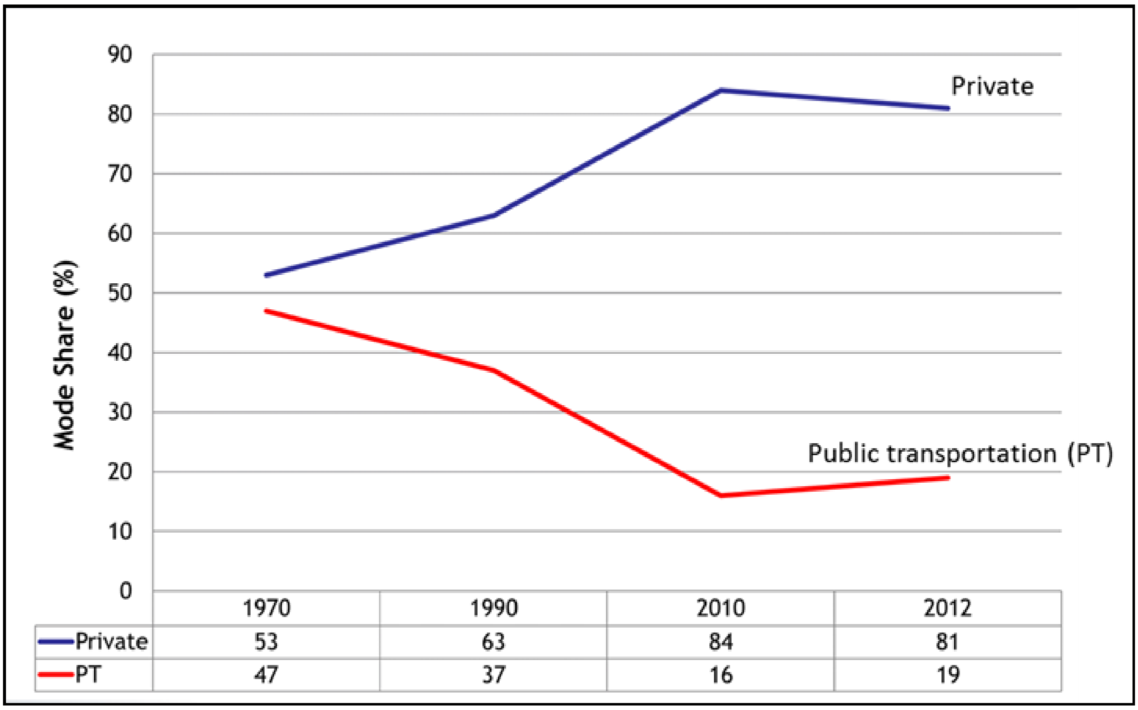

Figure 1. The trend of mode share for public transportation and private transportation. (Source: Suruhanjaya Perkhidmatan Awam Darat, 2013)

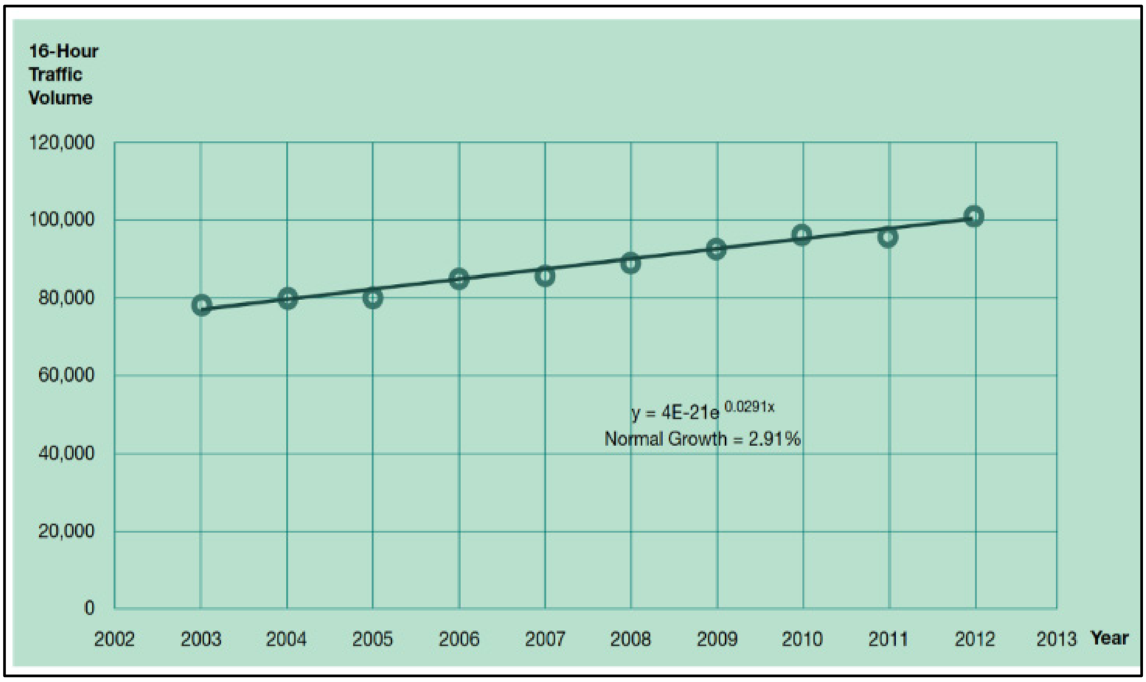

Figure 2. Normal traffic growth with an exponential trend in Malaysia (Source: Ministry of Transportation, 2012)

Figure 2 shows Malaysia's normal traffic growth rate (%/year) to be 2.91 percent. The years refer to the capacity years at which forecast traffic volume is equivalent to the computed road capacity [15]. The trend line shows that the growth of vehicles on the road is increasing at a faster rate. In this regard, it is predicted that the imbalance percentage of mode share will continuously cause the increase of road traffic volume in Kuala Lumpur for the upcoming years if no measures are taken to solve the problem.

To attain a sustainable transportation system as well as to reduce a congestion index in Kuala Lumpur, the government has set a vision to achieve a mode share ratio of 75:25 for private vehicles to public transportation. The current mode share in Kuala Lumpur is estimated at 20% to 30% [13,16]. In the next ten years, the demand for mobility is predicted to increase unprecedentedly as the city is growing at a faster rate in terms of population, infrastructure development, and economic activities [17]. Hence, this paper aims to optimise the congestion index and mode share of transportation values in 2030. The optimisation process was done on the six travel demand variables: bus route expansion rate, rate of park and ride (P&R), rail travel cost, bus fare subsidies, rail construction rate, and car parking charges. This research developed an integration of system dynamics (SD) and genetic algorithm (GA) approaches known as SD-GA model, to determine the best optimal value for congestion index and mode share through the optimisation analysis.

SD is one of the simulation approaches used to simulate the dynamic system that deals with feedback loops due to the interaction among disparate components in a system. It is an approach to capture the complex, non-linear, and dynamic behaviour of transportation systems [18,19,20]. SD modelling has been extensively used to simulate the transportation system. The approach was chosen because the transportation system is complicated, with a large number of interacting components and non-linear behaviour [19]. For instance, [21] created a microscopic freight transport simulation for cities based on SD to predict the medium and long term with this SD model. The qualitative SD approach of causal loop diagram is provided in this work, along with the internal structure of urban freight transportation and the players involved, as well as their interdependencies. The SD model created by [22] attempts to forecast CO_2 emissions from transportation sub-sectors in response to changes in social, economic, and technical variables, as well as policy. The model can be used to better understand the underlying causes that cause emissions in the road transportation sector, analyse and implement clean transportation regulations at the state level. Meanwhile, the SD model by [23] is a strategic decision-making tool for decision-makers working on the strategic development of public-private partnership programmes at a regional or nationwide level. The study by [24] intends to examine the impact of Brazilian policies on the urban transportation system, emphasising environmental, economic, and traffic characteristics for a case study in the Metropolitan Region of São Paulo. The findings of the SD model highlight the significance of policy implementation in reducing negative externalities in the urban transportation system. Besides, [25] developed a transit metropolis SD model based on the four subsystems of economics, society, environment, and transportation supply and demand in Nanchang City, China, in order to support the sustainable development of urban transportation. According to simulation results, Nanchang City would improve after the peak traffic congestion in 2022, showing that the transit metropolis' construction will benefit Nanchang. Finally, the SD model by [26] examined the impact of mobile app adoption on customer demand for taxi and e-hailing services as a quantifiable output. SD is a decision-experimentation strategy that allows policymakers to better understand how the transportation system will respond to their policies and the potential unintended consequences.

On the other hand, GA is an optimisation approach capable of searching for complex search spaces. Its characteristics do not get trapped into local optima, making it capable of searching for the best optimal solution [27]. Many studies applied optimisation approaches related to policy, planning, management, and operation in transportation. For instance, [28] developed a GA model to find an optimal combination of transportation planning strategies for multimodal transportation. The model's objective is to minimise the generalised cost of travellers given three decision variables which are bus fare, rail fare, and congestion toll price. [29] developed a Genetic Algorithm meta-heuristic model for clustering the different bus routes in order to reduce the total transportation cost over the routes. Finally, [30] used a GA model to compare two patrol strategies: overlapping patrol and non-overlapping patrol, to reduce the total average incident reaction time.

The methodology was further explained in the next section, while the results from the analysis of the SD-GA model are discussed in the subsequent section. This is followed by the conclusion and future work at the end of the paper.

2. Methodology

Model Description

The simulation is run for 30 years, starting from 2000 until the projection of the year 2030, since the selected time horizon is adequate to capture the important feedback on both short term and long term run [18,31]. In addition, the availability of historical data from 1990 was utilised as a validation tool and reference mode for the model. In particular, policy planning in the Malaysian Plan is endorsed every five years, which is adequate to capture policy changes in six terms. Furthermore, because data sources are only available on a yearly basis, the model uses yearly time steps.

The mode share of the model is disaggregated into three types of transportation modes, namely car, bus, and rail. In addition, for the duration of travel demand, the mode is desegregated into two peak hours that are 7.00 AM until 10.00 AM and 4.00 PM until 7.00 PM. This is because the historical trend from the statistics shows that the traffic congestion peaked during those periods. This explains that travel demand for public transportation is highly concentrated on morning and evening during these critical periods [10,32,33].

SD-GA Modelling Process

The dynamic transportation model was developed through the implementation of SD to address the problem of traffic congestion. The developed model was optimised using the integration of SD and GA approach termed as SD-GA model. The model works by varying the six travel demand variables to minimise the congestion index and mode share values, as presented in Figure 3.

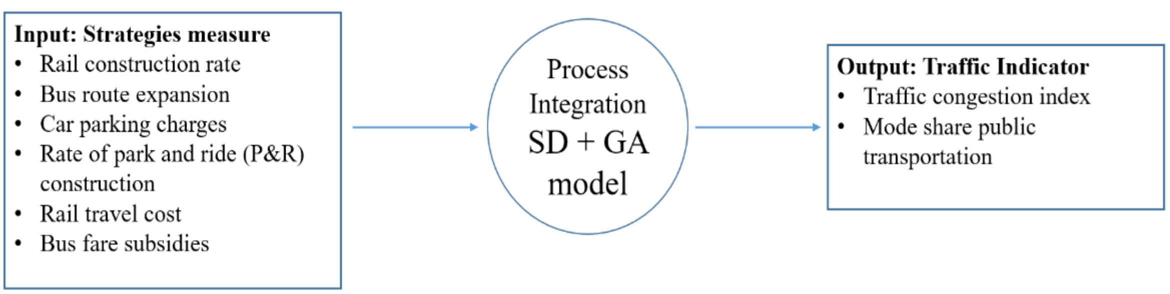

Figure 3. The input and output considered in the integrated model

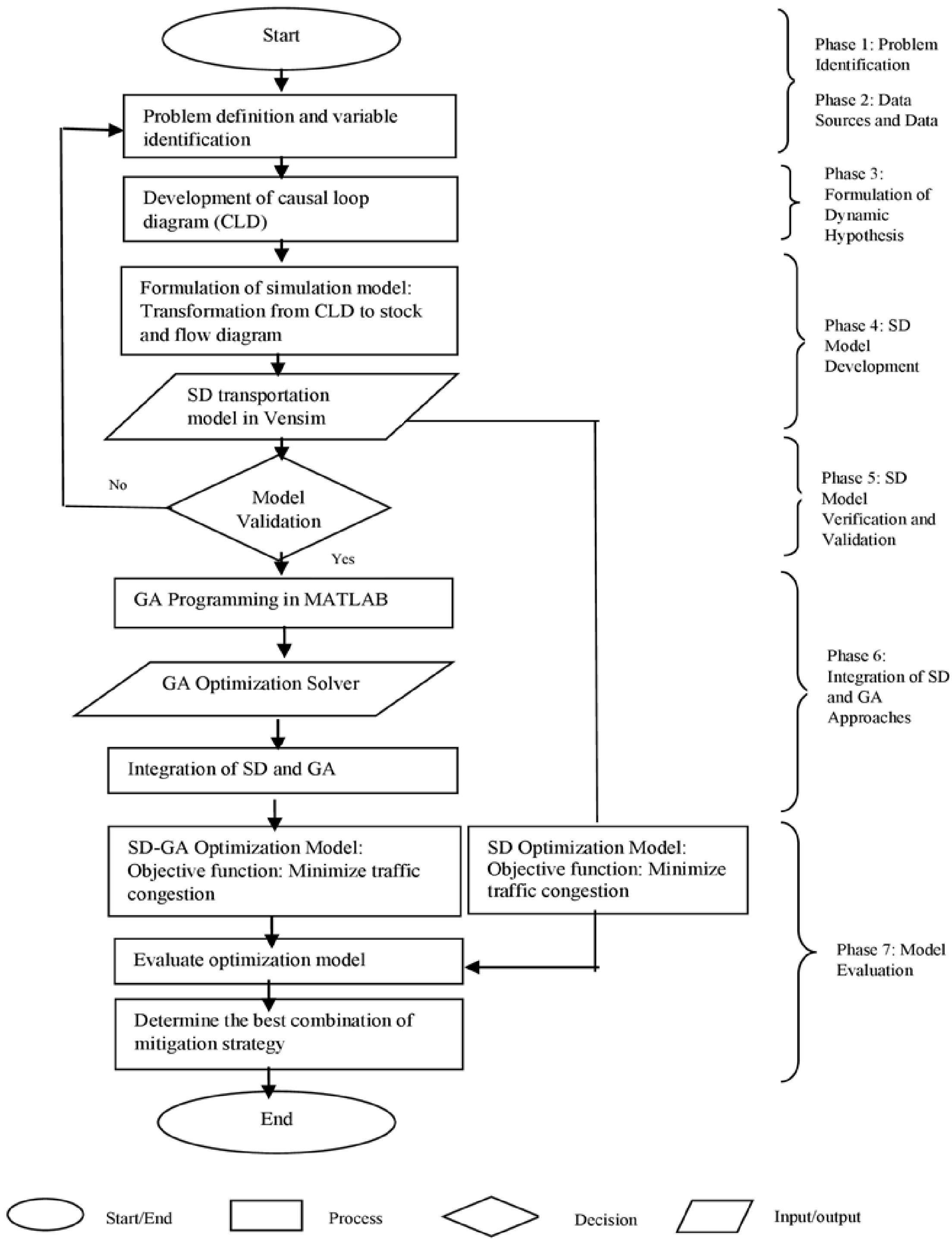

Figure 4. The research framework of the integrated SD-GA model

This research is conducted through seven phases of research activities as presented in Figure 4 in order to achieve the aim. The phases are; (1) problem identification, (2) data sources and data collection, (3) formulation of dynamic hypothesis, (4) SD model development, (5) SD model verification and model validation, (6) integration of SD and GA approaches, and (7) model evaluation.

In this research, the transportation system was modelled using the integration of SD and GA approaches. Firstly, the dynamic model was built using Vensim DSS 6.3 software to develop an understanding of the current and future conditions of the traffic congestion index in Kuala Lumpur. For the GA optimisation module, a customised programing written in MATLAB was constructed. Vensim and MATLAB are linked via Vensim Dynamic Link Library (DLL) to integrate both approaches to meet the research objective. The external function DLL was decompiled into C programming and compiled with a C-wrapper. Subsequently, the MATLAB compiler reads the external function DLL, which is responsible for getting the input and output data back and forth from Vensim. Consequently, the program runs in parallel, where MATLAB reads the input and sends back the output from Vensim through a graphical interface. The general simulation and optimisation of SD-GA architecture are shown in Figure 5.

SD Causal Loop Diagram

In SD, the causal loop diagram (CLD) is a tool used to map out the working mechanism of the system as well as to show the relationship and feedback of the interrelated elements [20]. Figure 6 shows the CLD for the transportation system. This CLD diagram demonstrated how travel demand strategies influenced the traffic congestion index and mode share of public transportation from a cause and effect perspective. The diagram was developed through a thorough literature review and based on data gathered from a variety of government reports on urban transportation

From the CLD, increasing the road construction will attract more travellers to utilise the roads, leading to more congested roads. Consequently, the short-term strategy of building more roads to combat congestion will create a spiral effect known as the Downs Thomson paradox [34]. On the other hand, the public transportation vicious circle shows that improving the public transportation facilities attracts commuters to choose as a medium of transport [35, 36]. In return, revenues generated from the fare benefit both the government and service provider to improve the facilities that could attract more passenger per trip.

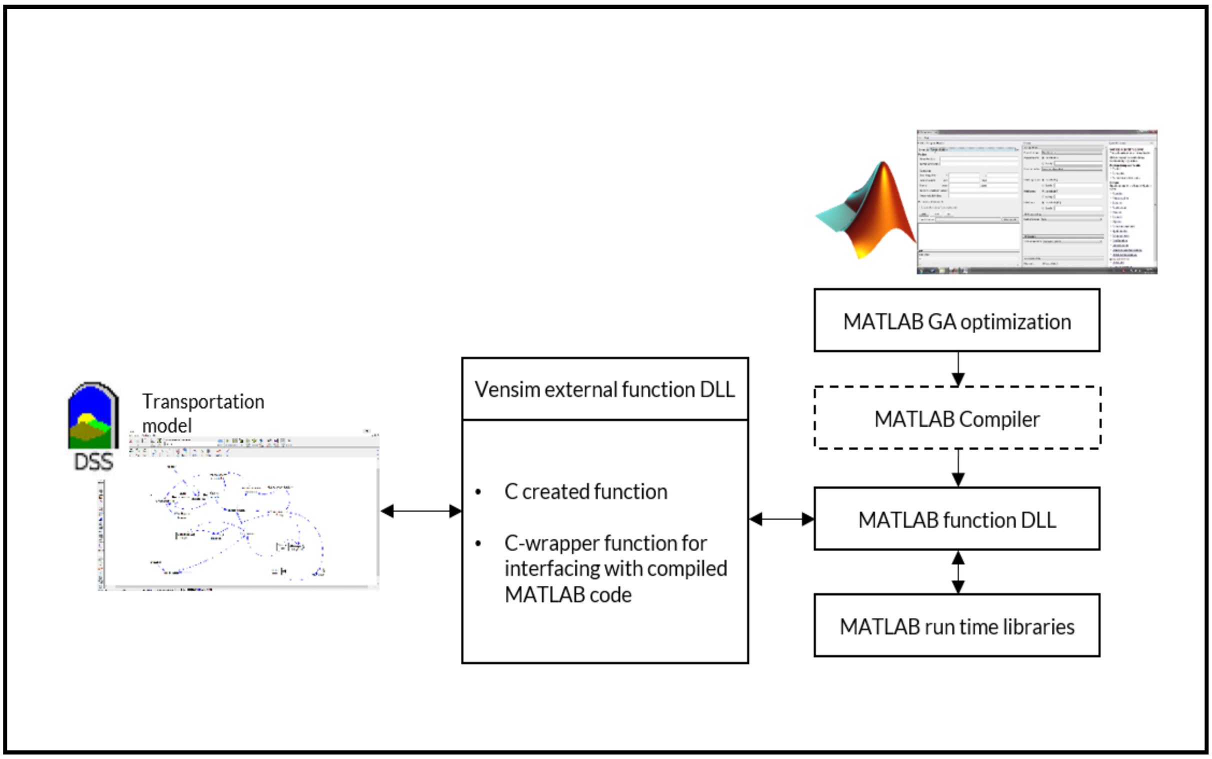

Figure 5. The general simulation and optimisation of SD-GA architecture

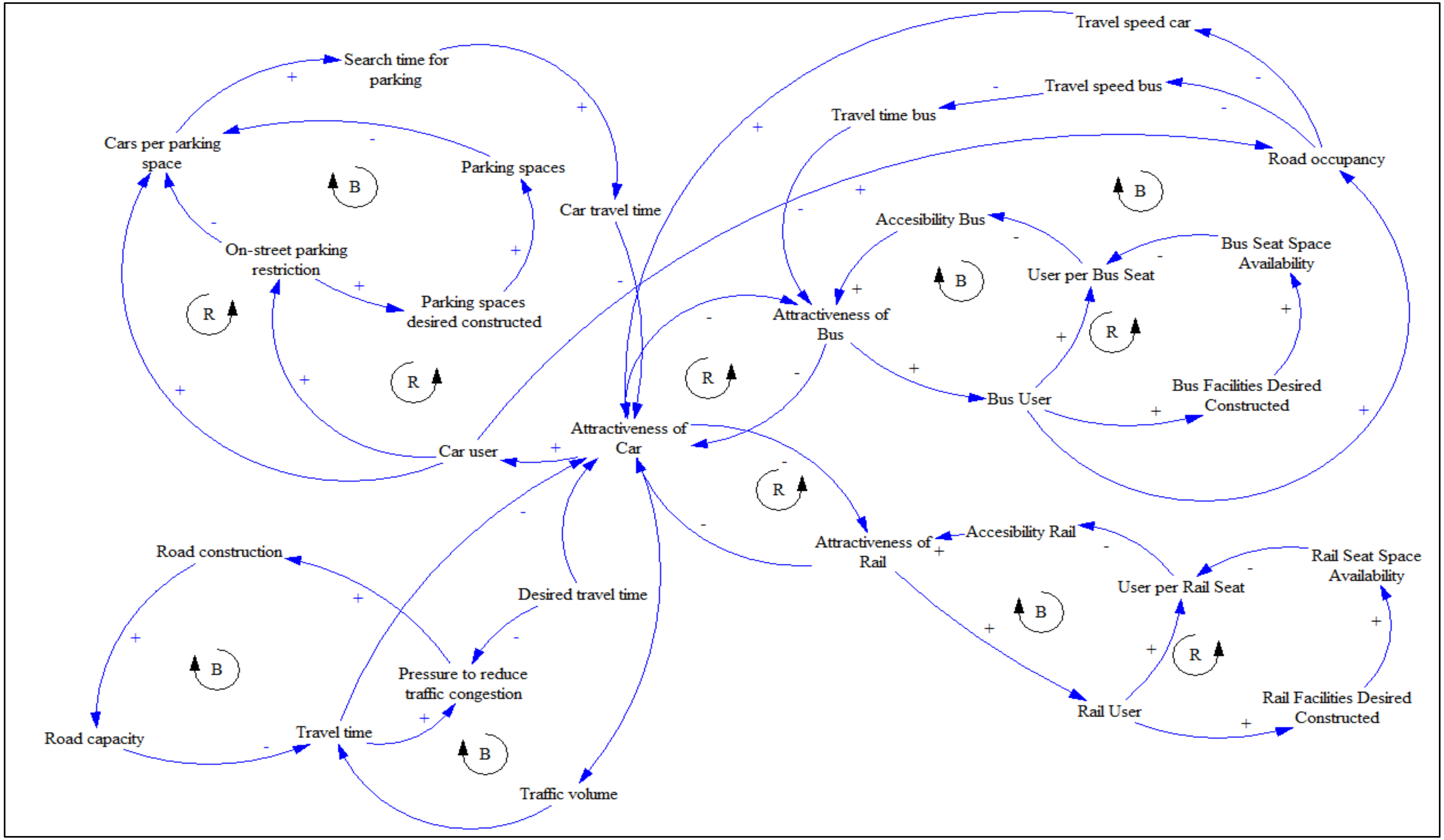

Figure 6. The CLD for the transportation system

However, suppose the service provider cannot serve the increasing demand; this will reduce the user per seat, eventually decreasing the accessibility of the public transportation to the user. Thus, this discourages commuters from using public transportation and switching to a private vehicle for a more convenient journey. This feedback loop applies to both bus and rail providers. Besides that, car parking charges can be imposed to tackle the higher usage of private vehicles compared to public transportation [37]. This can be explained by the parking space crowding loop. The general idea is to decrease the parking space for private vehicles and increase the parking space for public transportation users at the park and ride facilities.

For private vehicle users, limited parking space will increase the time searching for parking, thus increasing travel time. An increase in travel time will decrease the attractiveness of private vehicles, which ultimately increases the attractiveness of public transportation. On the other hand, in the scenario of park and ride for public transportation users, ample space for parking will reduce the time searching for parking and reduce the travel time. This will attract more people to use public transportation due to the convenience of searching for parking spaces. Apart from that, the travel speed loop represents the long-term effects of the travel speed on the attractiveness of using vehicles caused by traffic congestion.

Vehicles that use the road are cars and buses [20,38,39]. When the road occupancy decreases, the travel speed decreases, increasing travel time and reducing the attraction of using the mode of transportation. Table 1 summarises the CLD with the arrow symbol to highlight the relationship among the affected variable towards another variable. A positive sign shows the relationship in the same direction, while a negative sign shows the relationship in the opposite direction.

Table 1. The summary of the feedback loop

Type of Loop	Description
Road Construction Loop	Congestion->[+]road construction->[-]travel time ->[+] Attractiveness-> [+] road user -> [+] Congestion
Parking Space Crowding Loop	1. Car User -> [+] users per parking space -> [+] time search parking -> [+] travel time -> [-] attractiveness of car -> [Car user] 2. Car User -> [+] parking construction -> [-] users per parking space [+] travel time -> [-] attractiveness of car -> [Car user] 3. Car User -> [+] On street parking restriction -> [+] users per parking space [+] travel time -> [-] attractiveness of car -> [Car user]
Public Transportation Vicious Cycle Loop	1. Rail user -> [+] rail facilities construction-> [+] rail seat -> [-] user per rail seat -> [-] accessibility -> [+] rail attractiveness -> [+] rail user 2.Bus user -> [+] bus facilities construction-> [+] bus seat -> [-] user per bus seat -> [-] accessibility -> [+] bus attractiveness -> [+] bus user
Travel Speed Loop	1. Car User -> [+] road occupancy -> [-] travel speed -> [-] travel time -> [-] car attractiveness -> [+] Car user 2. Bus User -> [+] road occupancy -> [-] travel speed -> [-] travel time -> [-] bus attractiveness -> [+] bus user

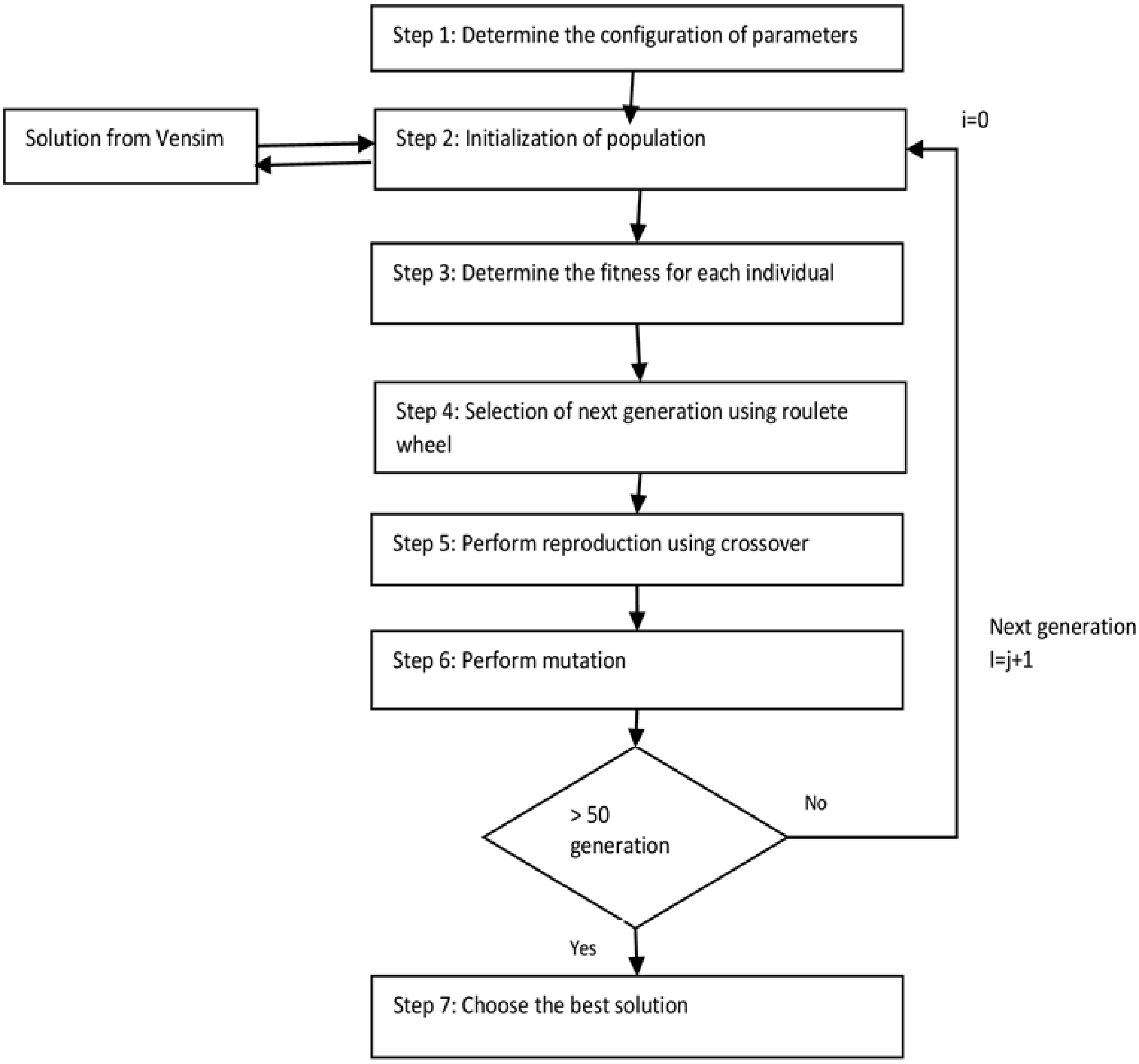

Figure 7. Workflow of the GA on the dynamic transportation model

Model Integration

Once the SD transportation model has completely been modelled, the development of GA was the second stage of the model development. GA approach was applied to find a combination of optimal travel demand variables to mitigate traffic congestion in Kuala Lumpur. GA is an optimisation search approach that is inspired by the evolutionary biology process. Likewise, GA mimics the process of chromosome reproduction that includes crossover, selection, and mutation of the chromosomes. The concept of evolution is that the process evolves at each iteration producing a better generation [27].

This section explains the GA process applied in this research according to the seven steps mentioned in Figure 7.

The first step in the GA process is defining the configuration for each process. Next, the population was initialised. An individual solution generated by GA is known as the chromosome, and a set of chromosomes is known as population. A chromosome is a string that is made up of genes [40]. The chromosome was undergoing an evaluation of its fitness function to measure the suitability of the solution generated by GA based on the objective function of the problem. Based on the fitness score from the evaluation, a pair of chromosomes was selected. These chromosomes are mated through a process known as crossover that produces new chromosomes. The selected chromosomes are called parents, and the new chromosomes reproduced are called offspring. The pseudo-code for the genetic algorithm process is the gene recombination of their parents. The next step is the mutation that changes the value of the genes. The crossover and mutation process is controlled by a crossover rate and mutation rate, i.e., 0.50 generations that have been defined in step 1. Finally, the best solution was chosen based on the objective function's fitness score, which targeted for the lowest traffic congestion index. The pseudo-code for the GA is shown in Figure 8.

Once the GA has completed one iteration, the result was sent back to the Vensim model to run the simulation. Finally, the output from the Vensim was retrieved by MATLAB to run the GA process. This is how SD and GA approaches were integrated and known as the SD-GA model.

3. Results and Discussion

Results of the best-optimised value for the chosen variables are presented in Table 2. The optimised values (in the second column) were compared with the base run value (first column). The base run is the model that represents the real-world transportation system's behaviour, characteristics, and variables.

This research has experimented with different configurations of GA by changing the parameter setting for crossover and mutation to obtain the best optimisation solution. This study runs the optimisation analysis for four SD-GA models, namely SD-GA1, SD-GA2, SD-GA3, and SD-GA4. The GA models are the permutation of the GA configuration of mutation and crossover. At the same time, as though using a roulette wheel, the chromosome selection remains the same in all combinations.

```
Generate a random population                          //Initialization

Start counter                                         //Iteration

While the counter less than number of generation

{

       Evaluate the fitness of each chromosome    //Evaluation

       Rank all chromosome

       Calculate Selection probabilities                 //Determine

probabilities

       Generate Mating pool

       Crossover of mating pool

       Mutation

}

While population size<max:                            //size check

              Select two best populations

              Create new objects

              Evaluate and place in population //breeding
```

Figure 8. The pseudo-code for the genetic algorithm process

Table 2. Result of SD-GA and SD base run for parameter values

Variables	Base run	SD-GA2	Percentage difference
1. Bus route expansion (1/year)	0.0342	0.0753	+120.18%
2. Rate of P&R construction (1/year)	0.144	0.312	+116.67%
3. Rail travel cost (RM)	8	5.77	-27.88%
4. Bus fare subsidies (%)	0.0737	0.1036	+40.57%
5. Rail construction rate (1/year)	0.046	0.0743	+61.52%
6. Car parking charges (RM)	9	10.12	+12.44%

Compared to all (SD-GA1, SD-GA2, SD-GA3, SD-GA4), it is found that SD-GA2 provides the best results in achieving the targeted outputs of mode share and congestion index. Referring to Table 2, the rate of bus route expansion shows the highest percentage difference of 120.18%, which indicates the most influential strategy to mitigate congestion in Kuala Lumpur. Therefore, the bus route infrastructure expansion should be increased to 7.53% per year. Moreover, the rate of park and ride construction appears as the second-highest percentage difference, i.e., 116.67%, with an optimised value of 0.312 per year. On the other hand, the rail travel cost should be reduced to RM5.77 while bus fare subsidies should be increased to 0.1036%. In contrast, the results suggested the parking charges should be increased to RM10.12 from RM9.

Figure 9 shows the trend of the changes in congestion index when the six variables were optimised. It is observed that trend of the congestion index had significantly reduced when optimisation analysis was applied to these variables. The findings from the analysis show that the best SD-GA model has improved the solution for congestion index reduction, which is from 1.1021 to 0.41367 by the year 2030 compared to SD base run. Besides that, Figure 10 shows an increasing trend of public transportation mode share, which indicates a balanced ratio of public transportation to private vehicles. Reduction in the percentage of private vehicles on roads decreases the level of congestion index. In summary, Table 3 presents the respective values of congestion index and mode share in 2030.

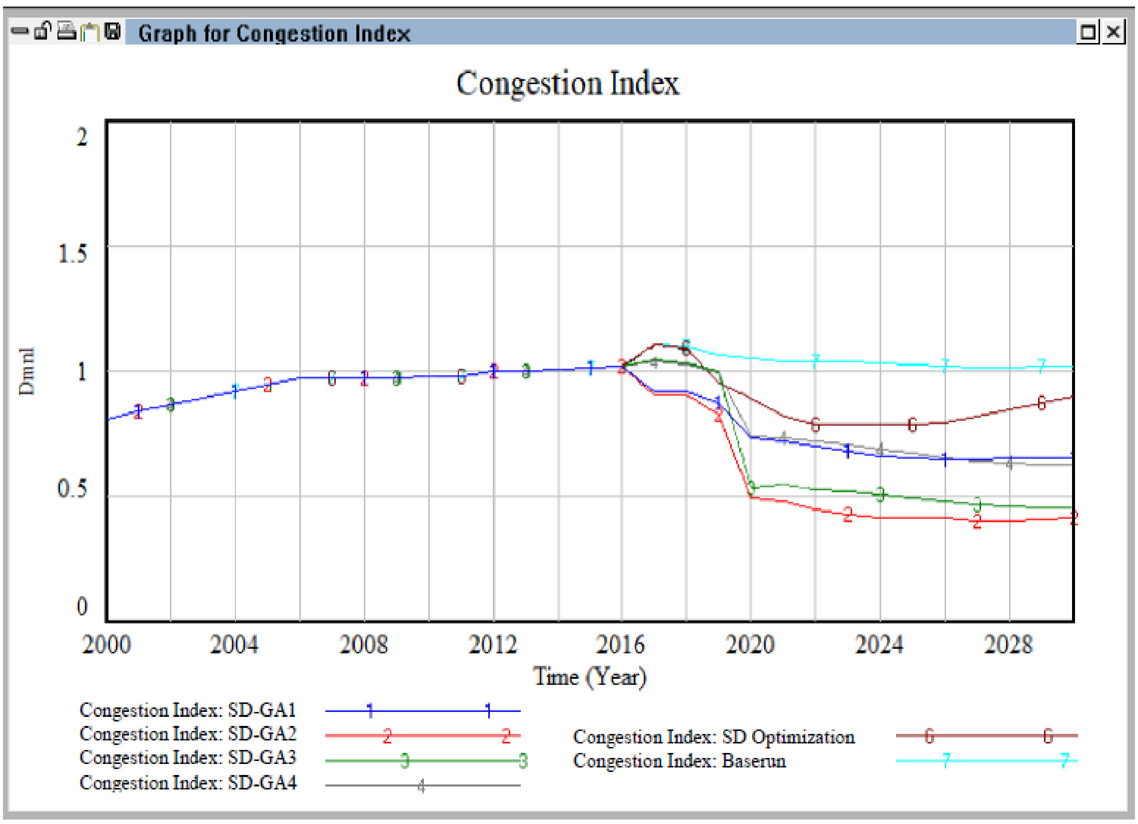

Figure 9. Comparison of the congestion index behaviour trends

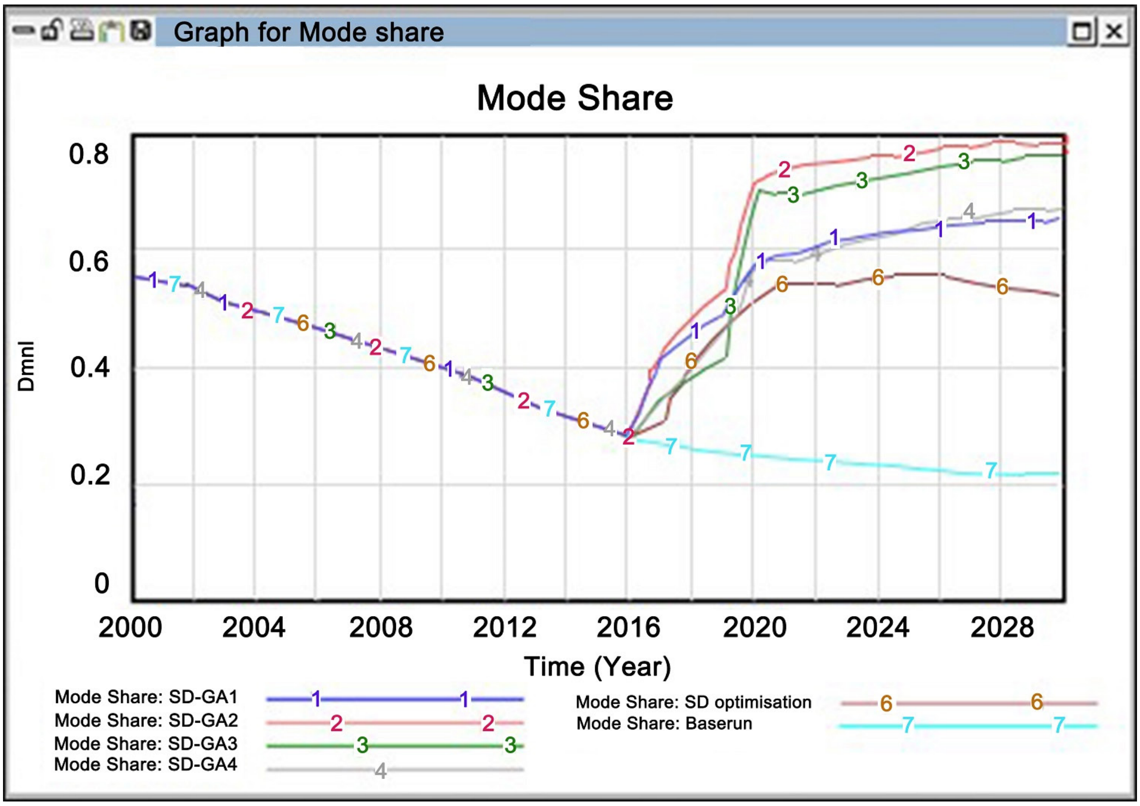

Figure 10. Comparison of mode share behaviour trends

Table 3. Comparison of mode share and congestion index results in 2030

Variables	SD-GA	SD Base run
Mode Share (%)	0.78412	0.217
Congestion Index	0.41367	1.1021

Results from the SD-GA optimisation model show an optimal value for congestion index of 0.41367 and a mode share for public transportation of 78%. The results complement the government's initiatives that aim to achieve a mode share of 50% by 2020 through the structured Plan of public transportation improvement. With the balance ratio of mode share between public transportation and private vehicles, a congestion index lower than 0.6 is achievable, which leads to a free-flow traffic condition [41].

4. Conclusions & Future Works

In this paper, the modelling process to minimise the transportation's congestion index and mode share in the urban area in Malaysia has been discussed. The modelling process starts with the development of a dynamic transportation model followed by the optimisation analysis using the integration of SD-GA approaches. Findings from this study highlighted one crucial point; the SD-GA model gives a better result in terms of achieving the targeted 50% of mode share and less than (<0.6) value of congestion index compared to the SD base run alone.

Although this research has achieved its objective, the proposed SG-GA model disregards the monetary value the government should consider in order to implement the best policy decision. Therefore, further research by incorporating cost-benefit analysis needs to be considered. With that, policymakers can choose the best strategies given a cost constraint, which is more practical in the real world.

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