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SYSTEM DYNAMICS MODEL TO DECREASE CONGESTION COST USING TRANSIT-ORIENTED DEVELOPMENT

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Abstract

Traffic congestion has had an impact on longer travel time and increased operational costs because vehicle speeds do not reach the speeds designed. Therefore, this research aims to decrease congestion costs using transit-oriented development (TOD). TOD is the integration of land use and transit to create a community that can walk within walking distance of a transit stop or station. It integrates people, jobs, and services to create efficient, safe, and comfortable services for traveling on foot or by bicycle, transit, or car. TOD can reduce the congestion cost

by encouraging housing locations near transit facilities, incorporating retail into regional development to attract customers from both TOD and main roads, as well as improving compatibility and connectivity of transportation systems. As a method used to reduce the congestion cost, we utilized system dynamics (SD) simulation model based on the consideration that SD can accommodate the dynamics complexity of several variables influencing the cost of traffic congestion. SD provides a framework to develop a causal loop diagram that allows SD as a tool to test the impact of various strategies and policies that affect the cost of traffic congestion. Some important factors that affect the cost of traffic congestion are congestion time per day and gross domestic product per capita. Simulation results of the scenario model after implementing the TOD show that the congestion cost per hour per capita is projected to decrease by an average difference of 53%. Congestion costs after applying TOD are projected to be around IDR 2025 per hour per capita in 2021 and IDR 451,800 per hour per capita in 2045.

Keywords

TOD, System Dynamics, Congestion Cost, Model, Simulation

1. Introduction

Traffic congestion can be defined as a delay in traffic conditions caused by the number of vehicle users exceeding the capacity that has been designed for existing traffic networks (Weisbrod, Vary, & Treyz, 2003). Traffic congestion results in longer travel times and increased operational costs due to vehicle speeds not reaching the designed speeds (Basuki & Siswandi, 2008). Transit-oriented development (TOD) is a type of urban development that aims to maximize residential, commercial, and entertainment spaces within walking distance of the public transportation node (Tan & Yi, 2019). TOD program can turn bus stations and terminals into multimodal transportation nodes that will integrate housing and public transportation. This program encourages greater transit passengers by maximizing access to public transportation and controlling the number of private cars. It can enhance the transportation network by encouraging transit ridership. TOD can create more transit choices for citizens, drive economic development, and mitigate congestion (Shinkle, 2012). It is expected that by using TOD program, it can reduce the traffic congestion cost.

2. Literature Review

This section demonstrates a literature review consisting of transit-oriented development (TOD) and the role of system dynamics method as a tool for model development to mitigate congestion costs.

2.1 Transit-Oriented Development (TOD)

Transit-oriented development (TOD) is the integration of land use and transit to create a community that can walk within walking distance of a transit stop or station (Neighborhood Planning and Zoning Department, 2006). TOD integrates people, jobs, and services to create efficient, safe, and comfortable services for traveling on foot or by bicycle, transit, or car. Some elements and characteristics of TOD for regional planning include (Neighborhood Planning and Zoning Department, 2006):

- Creating a compact development close to public transit;
- Focusing on pedestrians as a development strategy without excluding auto;
- Encouraging housing locations near transit facilities;
- Incorporating retail into regional development to attract customers from both TOD and main roads;
- Improving compatibility and connectivity with the surrounding environment;
- Introducing an integrated creative parking strategy;
- Developing a flexible TOD plan so that it can adapt to the conditions around it.

2.2 System Dynamics (SD) as a Tool for Model Development to Mitigate Congestion Cost

System dynamics (SD) is an approach in developing models and simulations to study complex and dynamic system behavior (Sterman, 2000). The structure of the system in the SD model is represented in a causal-loop diagram (Das & Dutta, 2013) which allows SD as a tool to test the impact of various strategies and policies in a system (Wei, Yang, Song, Abbaspour, & Xu, 2012). SD output models can be represented in graphical form using Ventana Simulation (Vensim) software (Zhao, Ren, & Rotter, 2011). SD has been used in the field of transportation systems in some literatures (Barlas, 2002; Springael, Kunsch, & Brans, 2002; Wegener, 2004).

Jia, Yan, Shen, & Zheng (2017) have developed an SD model to determine traffic congestion charges and subsidies. This paper introduces a subsidy mechanism and adopts a sensitivity analysis to explore a reasonable range of subsidies. He & Chen (2016) have built SD

model to analyze the current situation, reasons and impacts of traffic congestion by taking the city of Wuhan as an example. This paper analyzes the causal relationship between variables that have an impact on urban traffic congestion and provides a reference for the governance of traffic congestion problems to solve congestion problems. Vijayalakshmi & Umadevi (2014) have utilized system dynamics simulation to model the transit-oriented land use development of a rail corridor in Chennai. They found an increase in ridership of suburban service due to shifting users of the bus and personalized modes if the train transit capacity was enhanced. Here are some steps in developing the system dynamics model (Sterman, 2000): 1) defining the problem; 2) dynamic hypothesis development; 3) simulating the model; 4) model validation; and 5) scenario model development.

3. Base Model Development

This section demonstrates model development base on the existing condition which includes problem formulation of the existing system, causal loop diagram (CLD) development, as well as stock and flow diagram (SFD) development.

3.1 Problem Formulation of the Existing System

In this step, we need to determine the model boundaries and variables to ensure that the components of the model are in line with the model development goals. We have identified the model components (endogenous and exogenous variables) based on previous researches related to traffic congestion cost as seen in Table 1.

Table 1: Modelling Goal and Components (Endogenous and Exogenous Variables)

Modelling Goal	Model Components: Endogenous Variable	Model Components: Exogenous Variable
Reducing congestion cost	Congestion Cost (Litman, 2019)	Transit-Oriented Development (Vijayalakshmi & Umadevi, 2014)
	Reasons and Impacts of traffic congestion (He & Chen, 2016)	
	Traffic Congestion (Wang, 2010); (S. Chang & Choi, 2017);(Louf & Barthelemy, 2014).	

	Operating Cost of Congestion (Basuki & Siswandi, 2008); (Louf & Barthelemy, 2014)	
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3.2 Causal Loop Diagram (CLD) Development

A CLD is a qualitative method to describe the relationship between variables that influence the congestion cost. Congestion cost is influenced by congestion time and gross domestic product per capita (He & Chen, 2016); (Wang, 2010); (S. Chang & Choi, 2017); (Louf & Barthelemy, 2014) as seen in Figure 1. Transit-oriented development (TOD) will decrease congestion time (Vijayalakshmi & Umadevi, 2014). TOD can be conducted using several strategies such as encouraging housing locations near transit facilities, incorporating retail into regional development to attract customers from both TOD and main roads, as well as improving compatibility and connectivity of transportation systems.

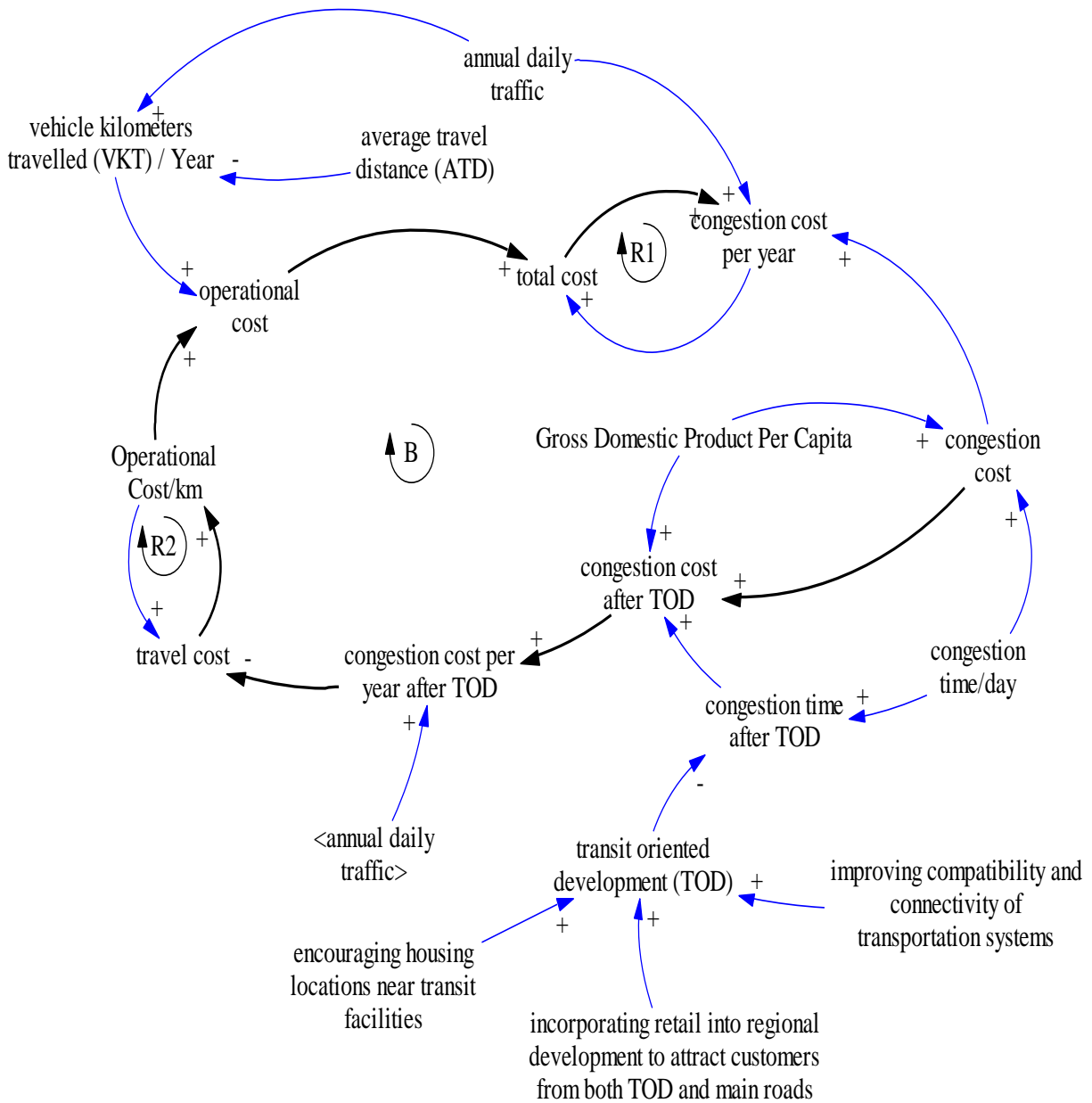


Figure 1: CLD of Transit-Oriented Development and Congestion Cost

CLD explains the system behavior by demonstrating feedback loops such as reinforcing and balancing loops. Reinforcing feedback loops (R) shows that changes in a node are in the same direction, whereas the balancing feedback loop (B) identifies a change in the opposite direction. The annual daily traffic and total cost influence the congestion cost per year. The increase in travel costs results in an increase in operational cost/km. By implementing the transit-oriented development, it will decrease the congestion time and congestion cost.

3.3 Stock and Flow Diagram (SFD) Development

SFD can represent the system structure by using symbols and specific components. SFD consists of stock variables, flow variables, auxiliary variables, constants, and causal influences between variables. SFD of congestion cost can be seen in Figure 2.

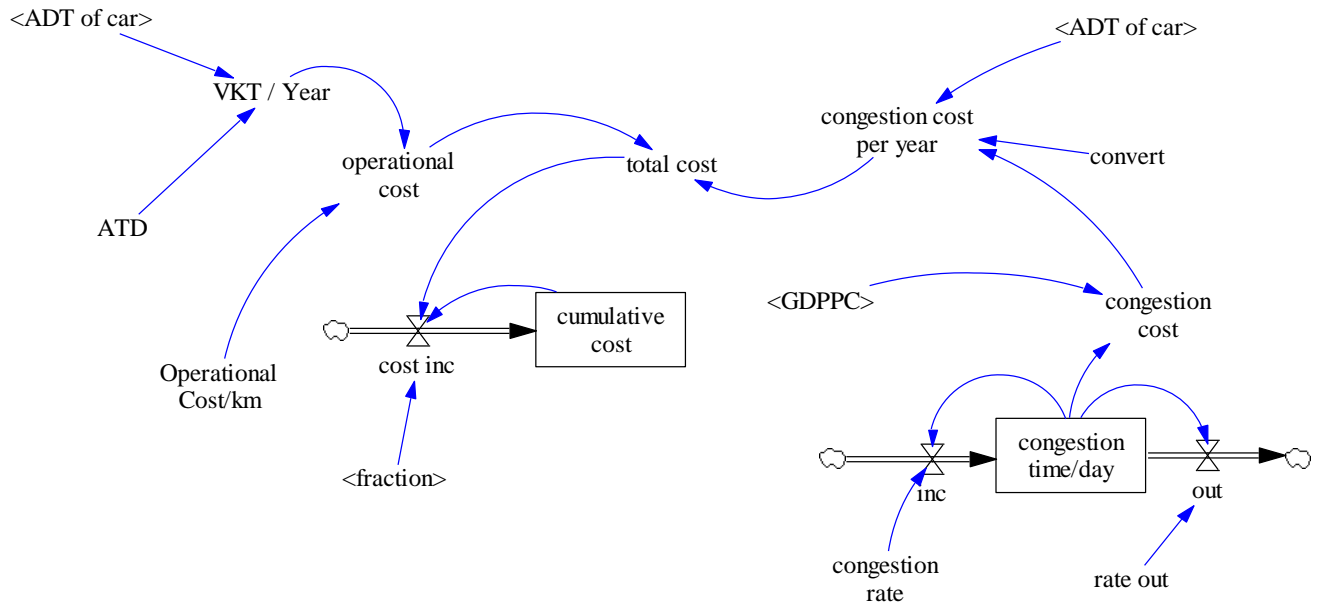


Figure 2: *SFD of Congestion Cost*

The model formulation of congestion cost can be seen in Equations (1) - (2):

$$CC(t) = \text{GDPPC}(t) / \text{WHY}(t) * \text{PCC}(t) * \text{CTD}(t) \quad (1)$$

$$\text{CTD}(t+1) = \text{CTD}(t_0) + \int \text{CRI}(t) - \text{CRO}(t) \quad (2)$$

where:

CC = Congestion Cost

GDPPC= Gross Domestic Product per Capita

WHY = Working Hours in a Year

PCC = The Percentage of Cost Congestion

CTD = Congestion Time per Day

CRI = Congestion Rate Incremental

CRO = Congestion Rate Output

4. Model Validation

Model validation is building confidence in the model as well as checking the model validity. Data and information are required during the time frame of the simulation. This time frame is set by considering the availability of data and the behavior of the system. The model will be valid if the error rate is $\leq 5\%$ and the error variance is $\leq 30\%$ (Barlas, 2002). The formulation of the error rate and error variance are shown in Equations (3) - (4).

$$E_r = \frac{[\bar{S} - \bar{A}]}{\bar{A}} \quad (3)$$

$$E_v = \frac{[S_s - S_a]}{S_a} \quad (4)$$

where:

\bar{S} = average rate of simulation

\bar{A} = average rate of data

A = data at time t

S = simulation result at time t

S_s = standard deviation of simulation

S_a = standard deviation of data

E_r = error rate

E_v = error variance

The error rates of the average daily traffic (ADT) of car and gross domestic product of region (GDPR) can be seen in Equations (5) – (8) :

$$\text{Error rate of 'ADT of car'} = \frac{[294,924 - 299,839]}{299,839} = 0.016 \quad (5)$$

$$\text{Error rate of 'GDPR'} = \frac{[306,641,500.5 - 313,422,356.3]}{313,422,356.3} = 0.014 \quad (6)$$

The error variances of the average daily traffic (ADT) of car and gross domestic product of region (GDPR):

$$\text{Error variance of 'ADT of car'} = \frac{[72,303.5 - 71,323.16]}{71,323.16} = 0.145 \quad (7)$$

$$\text{Error variance of 'GDPR'} = \frac{[133,471,837.4 - 133,277,990.4]}{133,277,990.4} = 0.001 \quad (8)$$

From the above calculation, all the error rates are less than 5% and the error of variances are less than 30%, which means that our model is valid. A comparison between the simulation results of the model and the historical data of the average daily traffic (ADT) of car and gross domestic product of region (GDPR) from the year 2006 – 2018 in Surabaya City can be seen in Figs. 3-4.

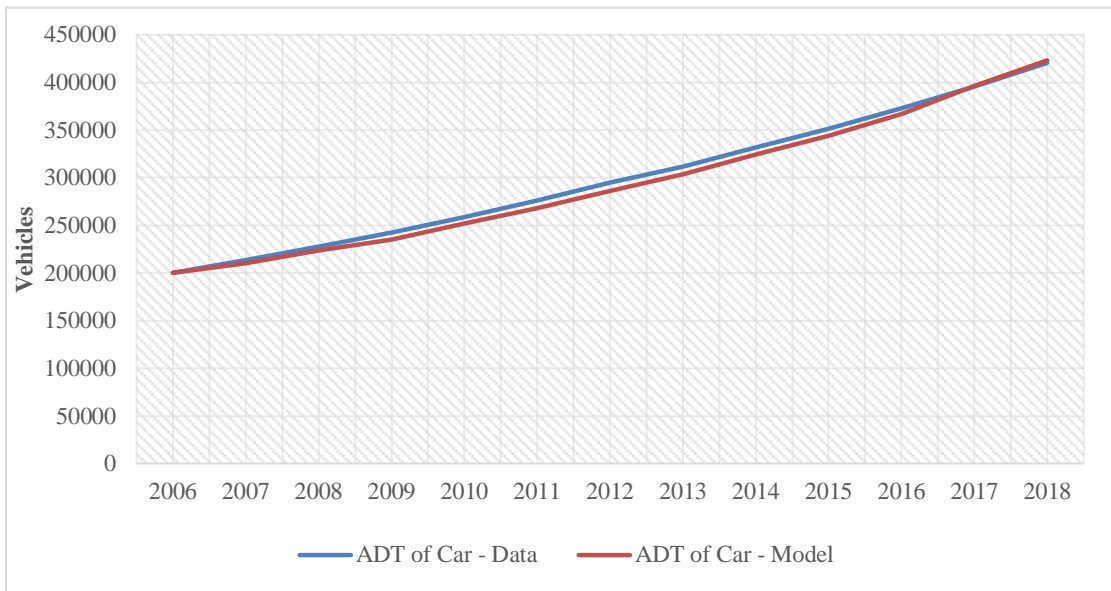


Figure 3: A Comparison between Model and Data of the ADT of Car in Surabaya City

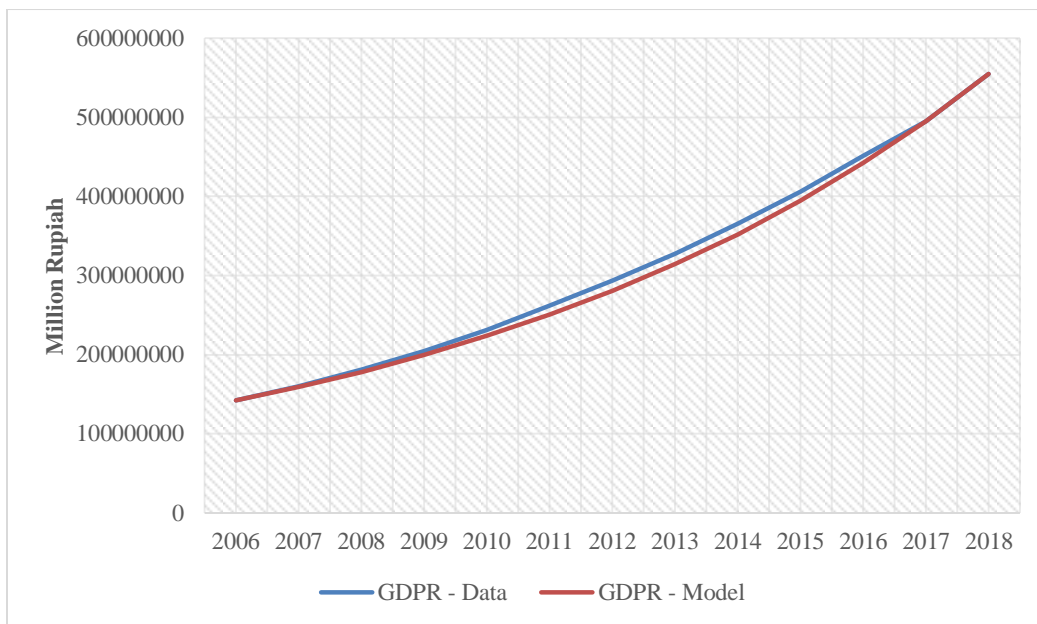


Figure 4: A Comparison between Model and Data of Surabaya GDPR

5. Results and Discussion

The simulation result of the congestion cost per capita can be seen in Figure 5. As we can see from Figure 5, congestion cost per capita continues to increase with the growth of 25.3%, so that in 2019 it reached IDR 2800 per hour per capita. This congestion cost is influenced by congestion time per day and GDP per capita. Congestion time per day tends to increase 14.5% per year as shown in Figure 6. Meanwhile, GDP per capita also tends to increase by 9.1% per year as shown in Figure 7. Congestion cost per capita is determined by these two factors.

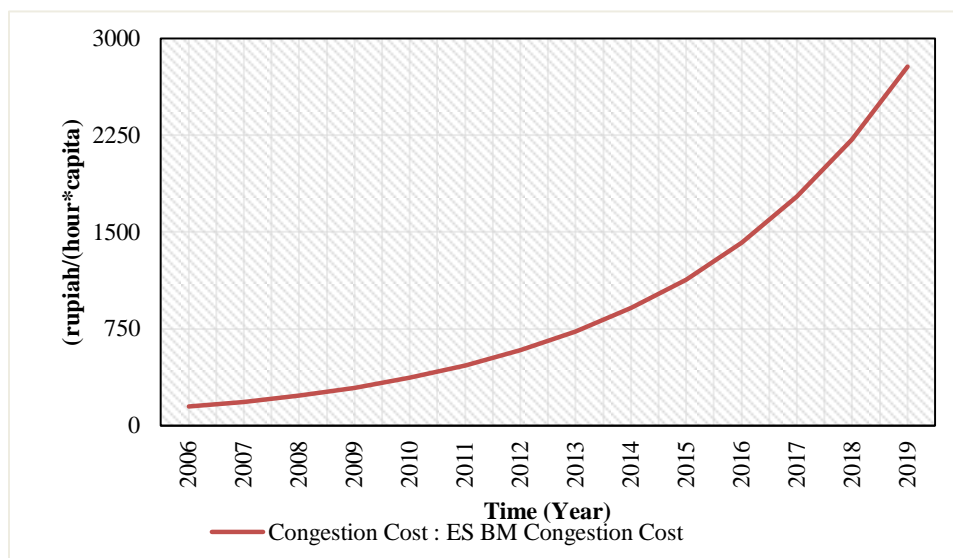


Figure 5: Congestion Cost per Capita in Surabaya City

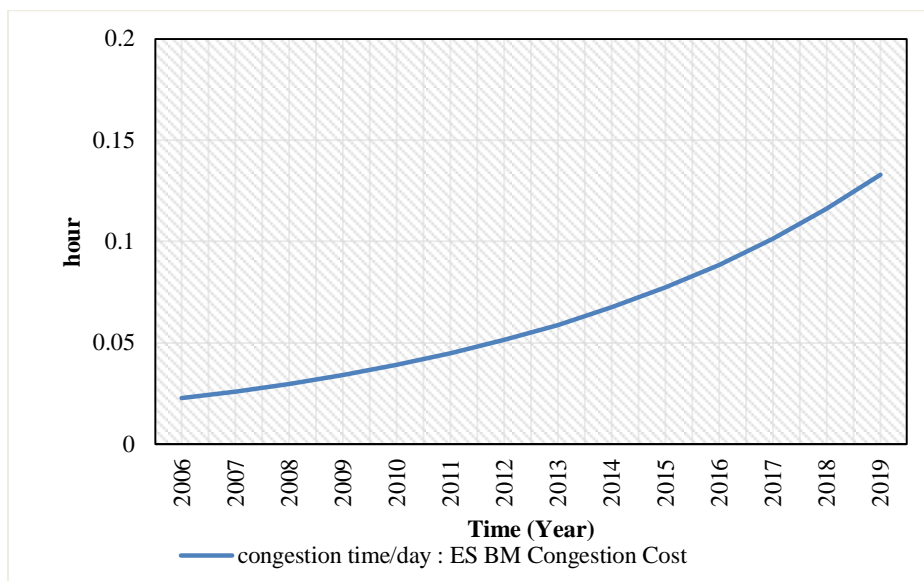


Figure 6: Congestion Time per Day

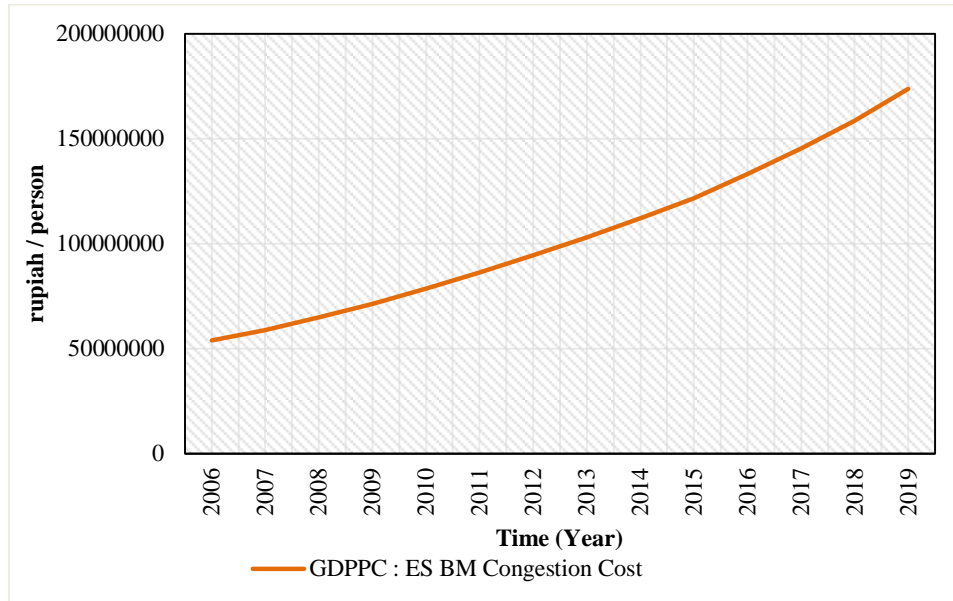


Figure 7: GDP Per Capita

6. Scenario Model Development

This section demonstrates a scenario model to reduce the cost of traffic congestion. The scenario is required to attain high performance through strategic flexibility and to anticipate the future with strategic real options by considering the business environment (Georgantzas, 2015). It can be conducted by modifying the model's structure and parameters (Suryani, 2011). The scenario model of reducing the cost of traffic congestion using transit-oriented development (TOD) can be seen in Figure 8. In this study, TOD can be conducted by encouraging housing locations near transit facilities, incorporating retail into regional development to attract customers from both TOD and main roads, as well as improving compatibility and connectivity of transportation systems.

By implementing the TOD program, the congestion cost per hour per capita is projected to decrease by an average difference of 53% as seen in Figure 9. Congestion costs per hour per capita after applying TOD are projected to be around IDR 2025 per hour per capita in 2021 and IDR 451,800 per hour per capita in 2045.

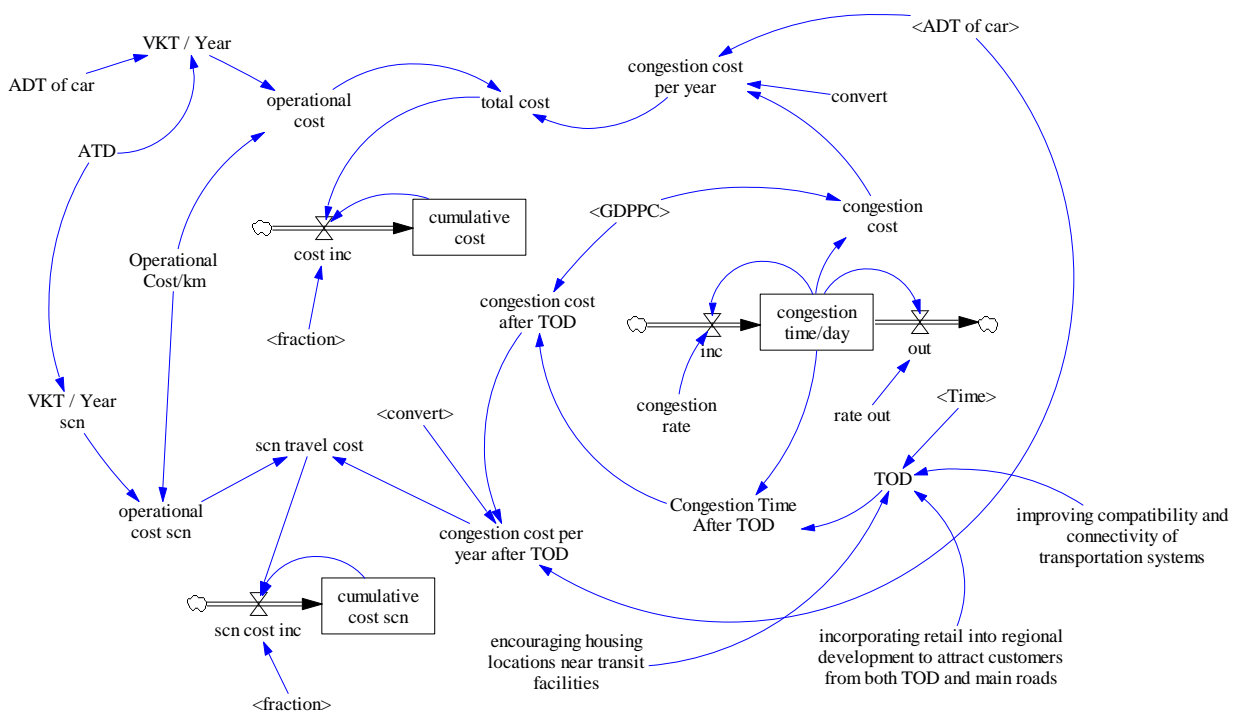


Figure 8: Scenario Model of Reducing the Cost of Congestion Using TOD

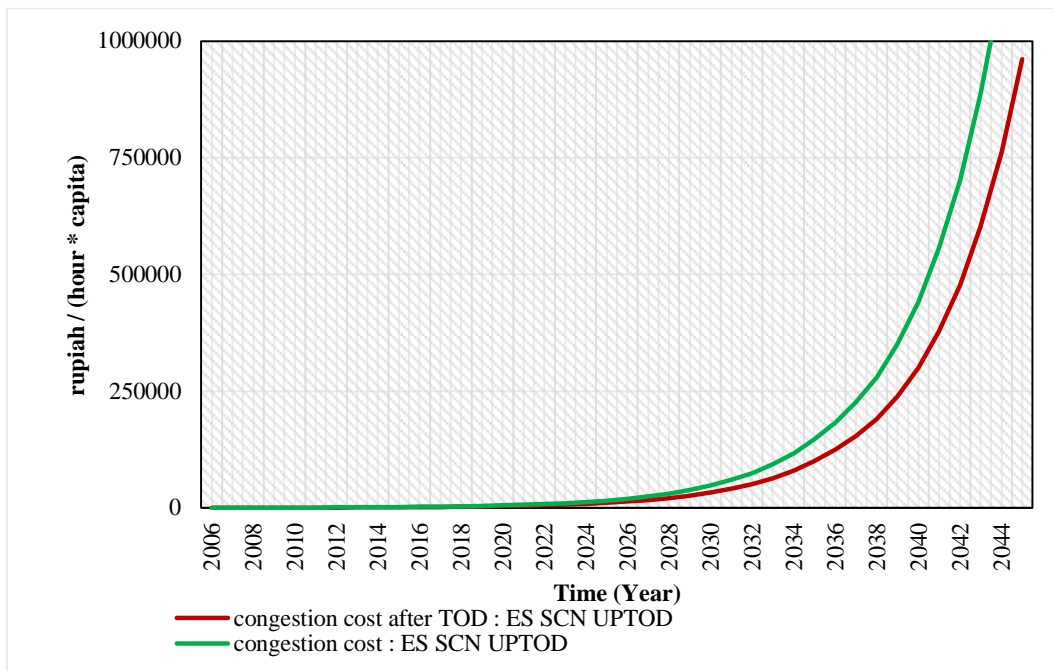


Figure 9: Congestion Cost per Hour Per Capita Before and After Implementing TOD Program

The annual congestion cost before and after implementing TOD program can be seen in Figure 10. As we can see from Figure 10, the average difference in annual congestion cost

before and after applying TOD is 53%. Annual congestion costs after implementing TOD are projected to reach IDR 817.2 billion in 2021 and are estimated at IDR 1,307 trillion in 2045.

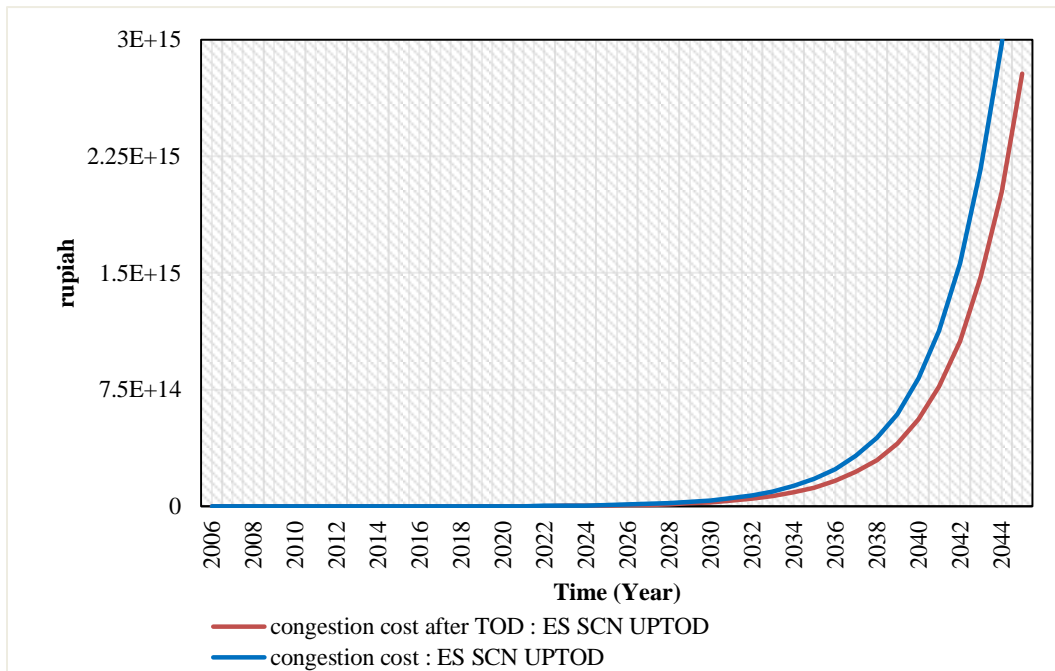


Figure 10: Annual Congestion Cost Before and After Implementing TOD Program

6. Conclusion and Further Research

This research was designed to provide a comprehensive assessment of reducing the cost of traffic congestion using a simulation model and scenario. To build the simulation model and develop the scenario, system dynamics (SD) was utilized based on the consideration that SD can accommodate the dynamics complexity of several variables influencing the cost of traffic congestion. The novel contributions of this research include: formulating relationships between variables that influence the cost of traffic congestion, building the dynamic behavior of congestion cost as well as developing scenario to reduce the congestion cost using transit-oriented development (TOD) program. This TOD program includes encouraging housing locations near transit facilities, incorporating retail into regional development to attract customers from both TOD and main roads, as well as improving compatibility and connectivity of transportation systems. Some important factors that affect the cost of traffic congestion are congestion time per day and gross domestic product per capita. This congestion cost and the average daily traffic of car will influence the annual congestion cost. Congestion cost per capita

continues to increase with an average growth of 25.3%, so that in 2019 it reached IDR 2800 per hour per capita. This congestion cost is influenced by congestion time per day and GDP per capita. Congestion time per day tends to increase 14.5% per year. GDP per capita also tends to increase 9.1% per year. The simulation results of the scenario model show that the congestion cost per hour per capita is projected to decrease by an average difference of 53%. Congestion costs per hour per capita after applying TOD are projected to be around IDR 2025 per hour per capita in 2021 and IDR 451,800 per hour per capita in 2045. Annual congestion costs after implementing TOD are projected to reach IDR 817.2 billion in 2021 and are estimated at IDR 1,307 trillion in 2045.

Further research that can be developed is congestion pricing that can accommodate pricing strategies to regulate demand and manage congestion without increasing the supply. Congestion pricing benefits drivers and business people by reducing delays and stress and increasing the accuracy of travel time predictions. Congestion pricing can increase transit speed and reliability of transit services, reduce costs for transit providers, improve the quality of transportation services without tax increases or large capital outlays, by providing additional revenue to fund transportation.

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