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Road Repair Delay Costs in Improving the Road Rehabilitation Strategy through a Comprehensive Road User Cost Model

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Abstract

This study delves into quantifying the adverse effects of road damage on users, particularly focusing on the increased travel time and consequent financial burdens stemming from delayed repairs. Utilizing a comparative method, the research underscores notable reductions in speed and prolonged travel times due to damaged roads, leading to substantial economic losses for road users. To streamline the estimation of road user costs (RUC), the study proposes a simulation model that incorporates varying traffic volumes and repair delays. This model demonstrates a high level of accuracy in estimating RUC, revealing heightened sensitivity to fluctuations in traffic volume and repair delays compared to agency costs. Consequently, the research underscores the imperative of implementing effective repair strategies to alleviate these impacts efficiently, thereby emphasizing the significance of timely infrastructure maintenance in mitigating financial burdens on road users.

Keywords: road damage, road user cost, traffic volume, repair delay, road rehabilitation strategy

1. Introduction

Roads are part of long-term transportation infrastructure built to support the mobility of goods and people. Roads are generally planned to have a service life of around 20 years or even more, but road authorities often find damaged roads before they reach their service life. The large number of overloaded vehicles causes a reduction in the service life of the road by around 6-8 years from its service life [1-2]. Overloads are caused by the road's inability to support loads beyond its capacity, causing the road to become vulnerable to damage. Several other factors can accelerate road damage, such as pavement age, increased traffic load, climate, material quality, subgrade conditions, soil compaction, and poor drainage systems [3].

Until now, these factors have often been ignored and caused the length of damaged roads to continue to increase. The existence of this damaged road certainly has several negative impacts, one of which is a decrease in driving speed [4-5]. The relationship between road damage is inversely proportional to vehicle speed. The vehicle speed will be smaller when the road damage is higher [6-7]. Low vehicle speeds increase travel time and exhaust emissions, so road damage has a direct negative impact on the economy and the environment. Not only does it reduce vehicle speed, but damaged roads also cause a significant reduction in traffic flow of 30%-40% compared to roads in good condition [8]. Road users often consider things like this trivial, even though they are economically very detrimental.

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Research related to road life cycle costs has begun to develop in recent years, where there are two main components: agency costs and user costs. In Sri Lanka, road user costs (RUC) vary from 13-45% of total road life cycle costs [9]. RUCs are often ignored, even though the phenomenon in Sri Lanka shows that RUCs constitute a relatively large proportion of the total road life cycle costs. One factor that significantly influences the size of RUC is traffic volume. Areas with high traffic volumes incur high RUC and can even exceed agency costs [10-11].

The phenomenon of implementing work zones is often used to evaluate the impact on RUC. In Indonesia, the implementation of work zones causes drivers to reduce their vehicle speed and impacts RUC by 160-210% of normal conditions [12]. Please note that RUC consists of several components, but the main components are vehicle operating costs (VOC) and value of time (VoT). When vehicle anti-bans accompany the implementation of work zones, the VoT tends to be more dominant than the VOC [13]. Apart from implementing work zones, the impact of road pavement conditions is often used as an object of study to analyze RUC. Worsening road surface conditions cause an increase in VOCs [14].

Damaged roads cause vehicles to experience a lot of shocks, and friction between the wheels and the surface becomes uneven. This situation causes an increase in fuel, oil, maintenance, spare parts, and tire consumption [15]. Damaged road conditions also often force drivers to reduce their speed. A decrease in speed causes an increase in travel time and impacts increasing VoT [16]. The increase in VoT varies greatly and depends on a person’s travel destination. Travelers whose travel purposes are for school, work, and business tend to experience a more significant increase in VoT [17].

Road maintenance and repair measures are one solution that can be implemented to overcome the negative impacts caused by road damage. Road maintenance and repair can optimize vehicle speed, an efficient method for reducing road damage’s environmental and economic effects [18]. This road repair and maintenance action has a positive impact on road users. There is a reduction in fuel consumption when a road is well maintained, which can reduce costs for road users [19-20]. The VOC component and well-maintained roads positively impact the VoT component. Well-maintained and repaired roads are proven to shorten travel time by almost 50% compared to when crossing damaged roads [21].

However, road repair and maintenance actions are often delayed due to a lack of awareness of road users and agencies, even though these actions can cause damage to a section of the road to worsen and can directly increase the economic losses experienced by road users. Estimating RUC can be important information for agencies in minimizing these losses [22]. On the other hand, road repair and maintenance actions also need to pay attention to the construction methods used. The development of road repair construction methods continues to go hand in hand with technological advances. The ultra-high-performance concrete (UHPC) overlay technology is one technology that allows road repair work to be carried out quickly [23]. Cutting the duration of road repair work can certainly minimize the negative impact on users and agencies. By referring to the calculation of RUC, rapid construction methods and carrying out work during periods of low traffic volume can be considered [24-25].

This research analyzes the negative impacts road users suffer when crossing damaged roads. It aims to develop an RUC model that can be used to estimate RUC based on traffic volume and duration of delays in implementing road repairs. On the other hand, this research aims to show how much costs increase due to delays in road repairs.

2. Research Methodology

The section elaborates extensively on the procedures and methodologies utilized in identifying the research location, quantifying the negative impacts of road damage, and developing the RUC estimation model. Through a meticulous approach, each phase is carefully delineated to provide a thorough understanding of how road damage affects users. From the initial selection of the research site to the detailed quantification of adverse effects, every step is crucial in uncovering the multifaceted nature of this issue. Moreover, the development of the RUC estimation model represents a significant culmination of these efforts, synthesizing insights gathered throughout the research process to offer a predictive framework for assessing user costs.

2.1. Research framework

This research is divided into four phases, as illustrated in Fig. 1. The first phase was carried out to identify the problem, determine the research objectives, conduct a literature study, determine variables, and collect data as the first step in the research. The second phase was carried out to analyze various negative impacts in the form of travel delays and vehicle queues experienced by road users due to road damage. The research calculates RUC, consisting of VOC and VoT by referring to Portuguese road user cost (PTRUC). In this phase, the VOC and VoT were also analyzed on varying lengths of road damage. The final phase of this research consists of establishing a model to estimate the amount of RUC due to the increase in traffic volume and the impact of road repair delays. in this phase, a comparison of the effects of road repair delays on user costs and agency costs is also carried out.

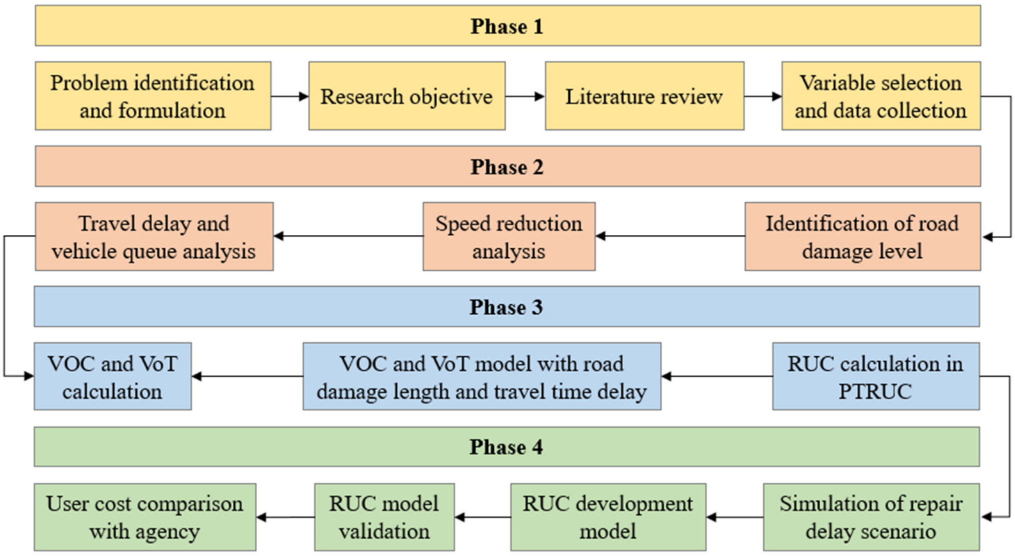


Fig. 1 Research workflow

Many notations are used in this research. This notation is widely used when estimating the magnitude of VOC, VoT, and RUC, as well as during the data analysis process and developing estimation models. Table 1 presents the terminology used in this research.

Table 1 Nomenclature section

Notation	Definition	Notation	Definition
a_i, b_i, c_i	regression coefficients for vehicle type *i*	m	travel purpose
CDV	corrected deduct value	$OR_{i,m}$	occupancy rate (person/vehicle)
Cd_i	depreciation cost for vehicle type *i* (IDR/km)	PCI	pavement condition index
Cf_i	fuel consumption cost for vehicle type *i* (IDR/km)	Q	vehicle queue (meters)
Cm_i	maintenance cost for vehicle type *i* (IDR/km)	RUC_i	road user cost for vehicle type *i* (IDR/km)
Co_i	oil consumption cost for vehicle type *i* (IDR/km)	s_i	average speed (km/h)
Cp_i	spare parts cost for vehicle type *i* (IDR/km)	T_i	duration of road repair delays (days)
Ct_i	tire consumption cost for vehicle type *i* (IDR/km)	TC_m	travel time cost ((IDR/h)/person)
Cx_i	tax cost for vehicle type *i* (IDR/km)	V_i	traffic volume for vehicle type *i* (vehicles/day)
D	travel time delay (second)	v	traffic volume (pcu/hour)
i	vehicle type	VOC_i	vehicle operating costs for vehicle type *i* (IDR/km)
IPC	income per capita ((IDR/day)/person)	VoT_i	value of time for vehicle type *i* (IDR/km)
L	length of road damage (meters)		

2.2. Pavement condition index

The identification of the level of damage to a road section can utilize various methods, including the pavement condition index (PCI) and the international roughness index (IRI). The PCI method is the most commonly used because of its easy application. This method visually evaluates the condition of a road section based on the type, level, and dimensions of damage by referring to the ASTM D6433-11 standard. The level of damage to a road section in this method is represented by a scale of 0-100, where a greater value indicates the better condition of the road section. In this method, the PCI value is obtained through the following equation:

$$PCI = 100 - \max(CDV) \tag{1}$$

where CDV is the corrected deduct value whose value varies according to the type, level, and dimensions of road damage identified visually on a road section.

2.3. Study area

This research was conducted on one of the roads in the industrial area, precisely on Jalan Raya Narogong, Klapanungal District, Bogor Regency, West Java, Indonesia. This road section is a two-lane, two-way, non-separated arterial road (2/2 UD) with traffic characteristics dominated by motorcycles (MC), followed by light vehicles (LV), medium vehicles (MV), and heavy vehicles (HV). On this road section, three segments were identified (Fig. 2), which experienced road damage with varying types and sizes of damage.

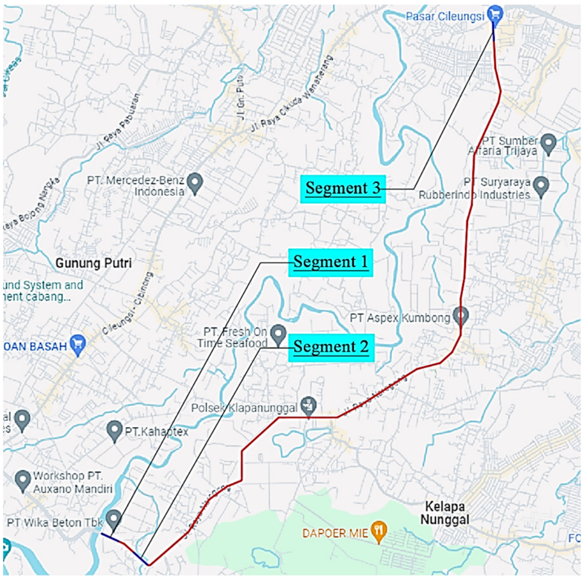


Fig. 2 Research location: Jalan Raya Narogong, Indonesia (Data Map © Google, 2024)

In Segment 1, damage to 48 meters of road was identified with types of damage in the form of raveling, polished aggregate, potholes and rutting; in Segment 2, damage to 32 meters of road was identified with the type of damage being raveling and polished aggregate; and in Segment 3, road damage along 65.7 meters was identified with types of damage in the form of raveling, polished aggregate, shoving, and longitudinal & transversal cracking. The PCI values for the three segments are 45-55, indicating a poor level of damage. In general, the characteristics of the three segments are described based on Table 2.

Table 2 Research location characteristics

Road segment	Road damage length (meters)	PCI		Vehicle proportion (%)			
		Value	Rating	LV	MV	HV	MC
1	48	52	Poor	13.7	6.0	2.6	77.7
2	32	55	Poor	17.1	6.3	2.5	74.1
3	65.7	48	Poor	20.4	7.2	2.2	70.2

2.4. Actual and normal travel speed

The spot speed method is used to obtain actual speed data for each vehicle that crosses the three road segments at the research location. In this research, actual speed measurements were carried out directly using a velocity gun where speed was measured when a vehicle was about to and when it crossed a damaged road. Apart from that, actual speed is also measured indirectly, where speed is obtained by dividing the distance by the travel time of each vehicle. These two methods were carried out to verify that they both produce relatively similar speed data. This actual speed data is used to compare how much speed reduction occurs when drivers cross damaged roads of various lengths compared to normal conditions. In this study, speed under normal conditions is represented by the speed limit on the three road segments, namely 40 km/h.

2.5. Road user costs

RUCs are costs that must be borne by road users when operating their vehicles on a road section. Generally, RUC consists of VOC, VoT, accident costs (AC), and tolls. This research focuses on the influence of changes in vehicle speed due to road damage so that only VOC and VoT are considered when calculating RUC. Tolls should be regarded as because the three road segments are not paid roads. Mathematically, the RUC calculation is expressed by the following equation.

$$\mathrm{RUC}_i = \mathrm{VOC}_i + \mathrm{VoT}_i \tag{2}$$

where RUC_i, VOC_i, and VoT_i, respectively, are RUC for vehicle type i (IDR/km), VOC for vehicle type (IDR/km), and VoT for vehicle type i (IDR/km). Meanwhile, $i = 1$ is a type of LV vehicle; $i = 2$ is a type of MV vehicle; $i = 3$ is a type of HV vehicle; and $i = 4$ is a type of MC vehicle.

2.6. Vehicle operating costs

VOC for each type of vehicle in this research is calculated from the total components of fixed costs and variable costs, which are expressed in IDR/km.

$$\mathrm{VOC}_i = \left(Cf_i + Co_i + Ct_i + Cp_i + Cm_i\right) + \left(Cd_i + Cx_i\right) \tag{3}$$

The first bracket in Eq. 3 represents the variable cost components of VOC, which consist of fuel consumption (Cf), oil consumption (Co), tire consumption (Ct), spare parts (Cp), and vehicle maintenance costs (Cm), respectively. The VOC variable cost component is calculated using the Pd T-15-2005-B guidelines in Indonesia. The second bracket represents the fixed cost components: depreciation (Cd), which is calculated using the straight-line depreciation method, and vehicle tax (Cx), which is obtained from the ratio of motor vehicle tax per year to the cumulative mileage of vehicles for one year. VOC estimation is carried out macroscopically, where each type of vehicle is represented by the most significant number of vehicle types for each kind of vehicle that passes on the three road segments.

2.7. Value of time

The VoT in this research is calculated for each type of vehicle by referring to the PTRUC model. This PTRUC model simplifies the HDM-4 model initiated by the World Bank [26]. The VoT equation is expressed as follows:

$$\mathrm{VoT}_i = \frac{1}{s_i} \times \sum_{m=1} \left(TC_m \times OR_{i,m}\right) \tag{4}$$

with,

$$TC_{m=1} = \mathrm{IPC} \tag{5}$$

$$TC_{m=2} = 0.25 \times \mathrm{IPC} \tag{6}$$

where s_i: average speed (km/h), TC_m: travel time cost ((IDR/h)/person) where $m = 1$ for travel in work time and $m = 2$ for travel in non-work time, $OR_{i,m}$: occupancy rate (person/vehicle), and IPC: income per capita ((IDR/day)/person). In this research, IPC is used because it is considered to represent the amount of money a person earns in an area. Based on the 2021 Bogor Regency Regional Government Implementation Report Summary, IPC at the study location is IDR 45,273,778.60 per year. The income is then converted into hours based on Article 28 Paragraph (1) of Government Regulation Number 35 of 2021, where the cumulative working hours for each person are 40 hours per week, so the IPC per hour is IDR 23,580.09. On the other hand, the amount of VoT is also influenced by the occupancy level of each type of vehicle. In Indonesia, the average vehicle occupancy for LV, MV, HV, and MC are 1.62, 1.58, 1.53, and 1.37, respectively.

2.8. RUC estimation model development approach

Research related to RUC continues to develop, one of which is developing a model formed using a regression method between RUC and traffic volume [27]. With several limitations, this model can estimate the amount of RUC quite accurately, even using simple data in the form of traffic volume. Unlike previous research, this research utilizes traffic volume variables and road repair delays as input for the RUC estimation model that will be developed. The RUC estimation model in this study was built using a simulation method where there is an increase in traffic volume along with the increasing duration of road repair delays, which impacts increasing RUC.

Observed traffic volumes and the absence of road repair delays are used as a database to develop the model. In this research, the increase in traffic volume was overcome by traffic growth in the study area of 1.36% per year. On the other hand, delays in road repairs are considered to be one of the causes of damage to a section of road becoming worse. This simulation also assumes an increase in the length of road damage of 0.01 meters for every 30-day repair delay. The simulation results then become data collection for developing the RUC estimation model, which is built using the multiple regression method.

3. Results and Discussion

This section provides valuable insights into how road damage affects travel behavior and costs. By revealing the relationship between road damage length, vehicle speed, travel time, traffic volume, and road repair delays, the study highlights the need for prompt repairs to minimize inconvenience to road users. In addition, the associated cost analysis emphasizes the importance of proactive maintenance strategies. These findings guide policymakers to prioritize timely repairs and improve the overall efficiency of the road network, making travel more seamless for road users.

3.1. Travel behavior toward road damage

Psychologically, every driver tends to reduce the speed of their vehicle when there are obstacles in front of them, including when they want to cross a damaged road. Through Table 3, this research reveals the intricate relationship between the length of road damage, vehicle weight, and vehicle speed. Most studies indicate that the impact of variations in the level and type of road damage is the cause of drivers reducing their travel speed. This research highlights the effects of variations in the length of damaged roads on vehicle movement, showing a substantial reduction in vehicle speed when crossing damaged roads. Through careful analysis, there are different variations in speed reduction for various types of vehicles and other damage lengths. When compared with average speed, there was a decrease in speed in Segment 1 of 23.44 km/h for LV, 23.61 km/h for MV, 25.11 km/h for HV, and 21.97 km/h for MC; Segment 2 is 20.44 km/h for LV, 20.66 km/h for MV, 22.20 km/h for HV, and 18.99 km/h for MC; and Segment 3 of 27.05 km/h for LV, 27.32 km/h for MV, 28.47 km/h for HV, and 24.50 km/h for MC.

Table 3 Speed reduction for each type of vehicle due to road damage

Vehicle type	Actual average speed (km/h)			Normal speed (km/h)	Speed reduction (%)		
	Segment 1	Segment 2	Segment 3		Segment 1	Segment 2	Segment 3
LV	16.56	19.56	12.95	40	58.59	51.10	67.62
MV	16.39	19.34	12.68		59.04	51.64	68.30
HV	14.89	17.80	11.53		62.77	55.49	71.19
MC	18.03	21.01	15.50		54.92	47.48	61.24

This relationship shows that the speed reduction is directly proportional to the length of the road damage, where the value will be more significant as the length of the damage increases. On the other hand, the exact relationship occurs between speed reduction and vehicle weight, where the reduction becomes smaller when the weight is lighter. The results of this speed reduction show that road users experience a significant impact due to the damage to the road. A substantial reduction in speed certainly has many adverse effects on road users. This research underscores the urgent need for proactive maintenance strategies to mitigate these negative impacts.

Moreover, this research highlights the potential of targeted interventions to alleviate speed reductions, with considerations such as road damage length and vehicle weight playing pivotal roles in shaping effective mitigation strategies. Although this research provides valuable insights, it is important to acknowledge limitations and opportunities for future research. Regardless of the empirical rigor used, focusing on a particular research location requires caution in generalizing findings to broader contexts. Additionally, certain confounding variables, such as driver behavior and weather conditions, may have influenced the results of this study, necessitating further investigation to validate the findings in this study.

3.2. Impact of road damage on travel time

Table 4 shows the direct negative impact of increasing travel time on road users when crossing roads in damaged conditions. In Segment 1, there is an additional travel time of 220%-270%; in Segment 2, there is an extra travel time of 190%-225%; and in Segment 3, there is an additional travel time of 255%-345% for each type of vehicle when compared to normal travel time. Speed has an inverse correlation with time, so the results are the opposite of the previous section, where the length of the road is getting worse, and the weight of the vehicle is getting bigger, causing a more significant speed reduction, which results in a more considerable increase in travel time. The results show that road damage causes an increase in travel time, which is often not realized by road users, even though, from an economic perspective, it is indirectly very detrimental.

Table 4 Delays Due to Road Damage

Vehicle type	Travel time of 75 meters with						
	Actual average time (second)			Normal time (second)	Added travel time (%)		
	Segment 1	Segment 2	Segment 3		Segment 1	Segment 2	Segment 3
LV	16.30	13.80	20.85	6.75	241.52	204.45	308.89
MV	16.48	13.95	21.35		244.19	206.67	316.37
HV	18.14	15.14	23.33		268.70	224.35	345.63
MC	14.98	12.85	17.39		221.87	190.35	257.58

This research explains the dynamics of vehicle queues due to reduced speed when crossing damaged roads, especially in high-traffic volume scenarios. Vehicle queues generally occur when the first driver reduces vehicle speed, forcing the drivers behind them to adjust their speed. The increase in traffic volume and the presence of obstacles due to road damage have resulted in queues of vehicles approaching the location of the road damage. As a result, longer queues of cars have the potential to cause more significant delays and have an impact on increasing costs for road users.

This research shows that the level of road damage does not substantially affect queue length; factors such as differences in the length of road damage and traffic volume show a significant correlation (0.689 and 0.704, respectively) with queue length. The following equation represents the relationship between queue length, road damage length, and traffic volume.

$$Q = -805.31 + 1.89 \times L + 1.04 \times v \tag{7}$$

where Q, L, and v respectively are the length of the vehicle queue (meters), the length of road damage (meters), and the traffic volume (pcu/hour). The relationship between these three variables is illustrated in Fig. 3, where there is a positive correlation between queue length, length of road damage, and traffic volume. Color changes from blue to red also respectively depict a similar condition where the length of the vehicle queue will be more significant when there is an increase in the length of road damage and traffic volume. The visualization shows the combined effect of these factors on queue length, highlighting the importance of strategic interventions to reduce congestion and minimize disruption to vehicle movements.

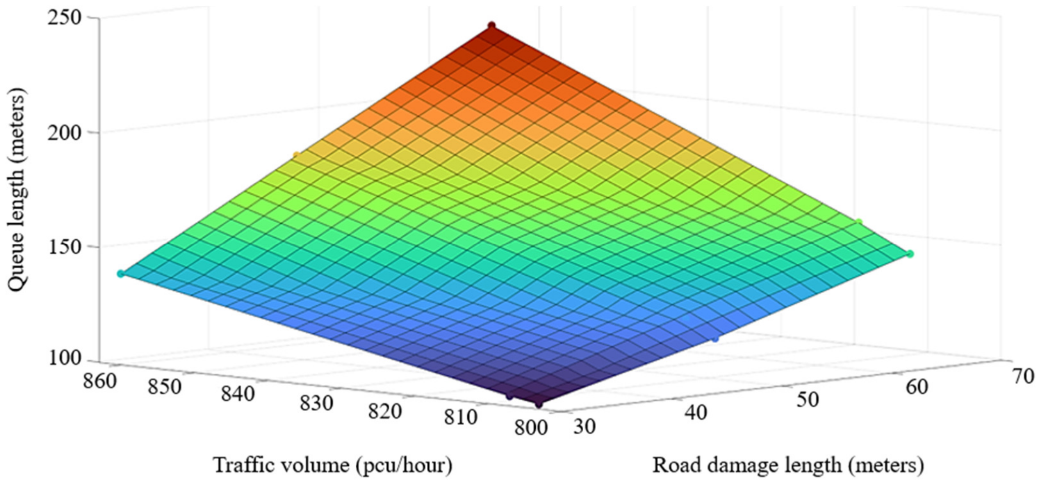


Fig. 3 Relationship between queue length and road damage length and traffic volume

3.3. VOC and VoT correlation with road damage length and travel time delay

Directly, damaged roads cause a lot of vibrations to be felt in the vehicle and increase travel time, which causes discomfort for road users. On the other hand, there are indirect costs that road users must bear due to this inconvenience. Many studies reveal that the level of road damage affects the amount of VOCs borne by road users. The increasingly severe level of road damage causes greater VOC. This research also reveals that other factors influence the amount of VOC, namely the length of road damage.

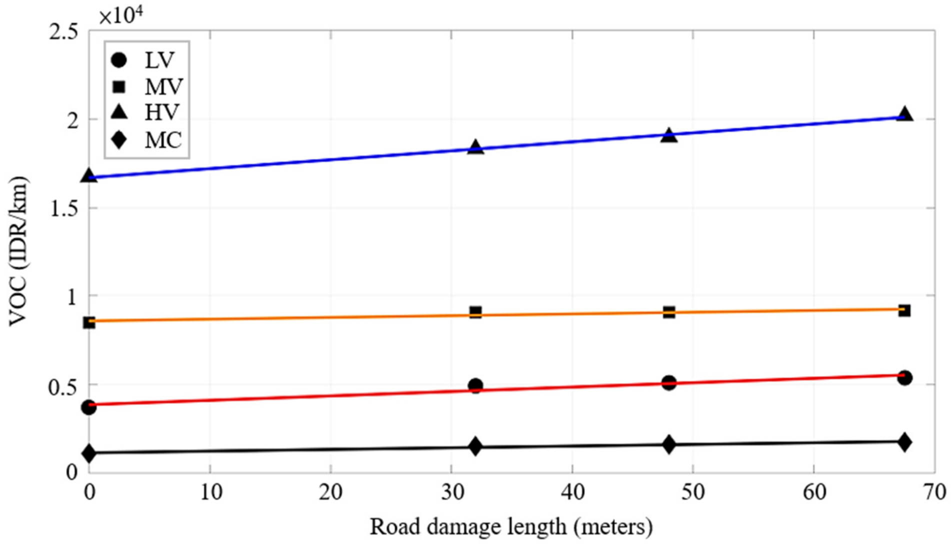


Fig. 4 Correlation of VOC with length of road damage

Fig. 4 illustrates the directly proportional correlation between VOC and the length of road damage. The figure also shows that the type of vehicle is also a factor that influences the size of the VOC. HV tends to experience greater VOCs than MV, LV, and MC. The following equation expresses the relationship between VOC and the length of road damage.

$$\text{VOC}_{i=1} = 24.69 \times L + 3871.8 \tag{8}$$

$$\text{VOC}_{i=2} = 9.84 \times L + 8586.3 \tag{9}$$

$$\text{VOC}_{i=3} = 50.55 \times L + 16695.0 \tag{10}$$

$$\mathrm{VOC}_{i=4} = 9.43 \times L + 1159.6 \tag{11}$$

where L is the length of the road damage (meters), Fig. 4 shows that the correlation between VOC and the length of road damage will continue to increase as the length of the damage continues to grow.

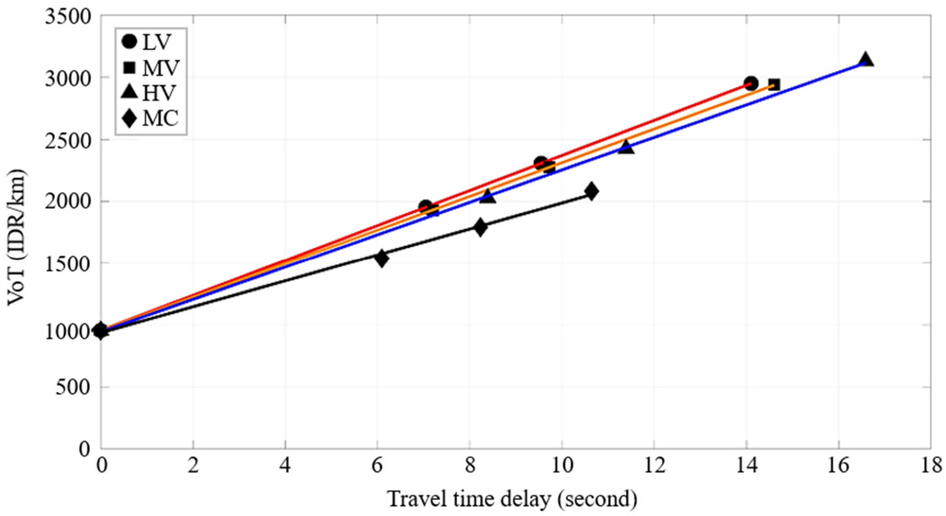


Fig. 5 VoT correlation with travel time delay

Drivers generally reduce their vehicle speed when approaching and crossing damaged roads. This condition has a direct impact on increasing travel time, which increases the VoT value. Fig. 5 shows the correlation between VoT and the travel time delay. The following equation shows this relationship:

$$\mathrm{VOT}_{i=1} = 141.48 \times D + 955.26 \tag{12}$$

$$\mathrm{VOT}_{i=2} = 135.89 \times D + 955.54 \tag{13}$$

$$\mathrm{VOT}_{i=3} = 130.99 \times D + 943.74 \tag{14}$$

$$\mathrm{VOT}_{i=1} = 105.07 \times D + 936.13 \tag{15}$$

where D is the travel time delay (second). Similar to VOC, this correlation shows a positive linear relationship, indicating that VoT will be more significant as the travel time becomes longer. When repair actions on a damaged road section are delayed for an extended period, the impact of the damage to the road can potentially increase RUC through the relationship between the two RUC components and the length of road damage. The amount of VOC and VoT will likely continue to increase along with the duration of the delay in road repairs.

3.4. Results of RUC calculation

There has been a lot of research regarding RUC due to road damage. The commonly used parameter is the road damage level represented by the PCI or IRI value. In contrast to previous research, this research uses the length of road damage as a novelty in analyzing its impact on increasing RUC. Table 5 in this study shows the significant costs that road users must bear due to road damage.

Table 5 Average road user cost calculation

Costs	Vehicle type			
	LV	MV	HV	MC
RUC ((IDR/km)/day)	7,459,380.65	4,271,317.21	2,970,013.02	14,138,306.63
VOC ((IDR/km)/day)	5,039,016.12 67.55% of RUC	3,367,369.37 78.84% of RUC	2,624,176.64 88.36% of RUC	6,721,752.02 47.54% of RUC
VoT ((IDR/km)/day)	2,420,364.54 32.45% of RUC	903,947.83 21.16% of RUC	345,836.38 11.64% of RUC	7,416,554.61 52.46% of RUC

The most considerable RUC contribution is MC because it has a dominant volume proportion compared to other types of vehicles. The RUC calculation of the VoT component shows a percentage that is significant enough to be considered when making decisions on the timing of road repair implementation. The most considerable VoT contribution is from the MC vehicle type, but this type of vehicle has the lowest VOC contribution compared to other vehicle types. On the other hand, for HV vehicles, the VOC value is much greater, but the VoT value is the lowest. In Fig. 6, the RUC components show dominant depreciation costs for LV vehicles, while fuel costs prevail for MV, HV, and MC vehicles.

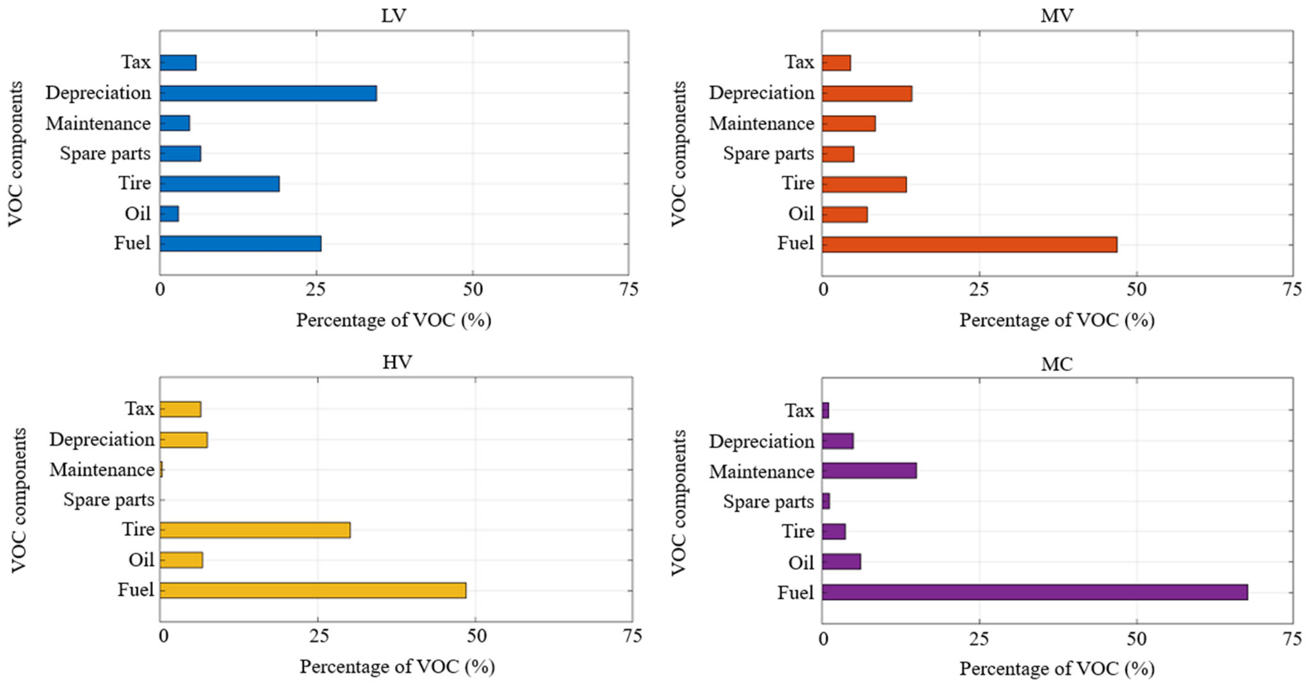


Fig. 6 Percentage of average VOC constituent components

The various negative impacts experienced by road users due to damaged roads have caused a significant increase in RUC (Table 6). The magnitude of the increase in RUC is in line with the length of road damage and vehicle queues, where Segment 2 experiences a minor rise in RUC compared to Segment 1 and Segment 3. The size of road damage, vehicle queues, and traffic volume influence the amount of RUC. The very significant difference in the volume of MC vehicles compared to the volume of LV, MV, and HV vehicles causes the increase in RUC to be more significant than that of LV, MV, and HV. The RUC for MC is the smallest compared to the others, followed by LV, MV, and HV. This value shows that traffic volume has a very significant role in the total RUC.

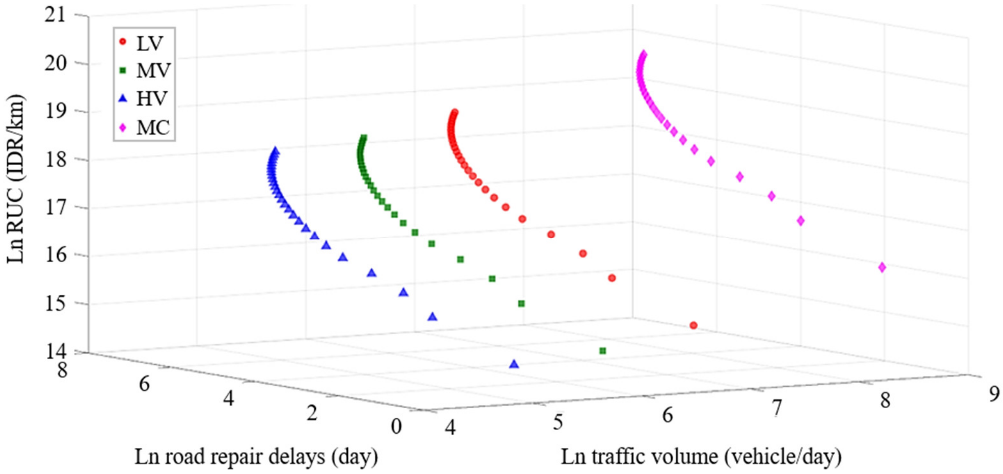
Table 6 Percentage increase in RUC against normal road conditions

Vehicle type	% RUC increase		
	Segment 1	Segment 2	Segment 3
LV	58.72	47.21	77.92
MV	20.81	16.75	27.99
HV	21.49	15.38	32.36
MC	77.65	59.30	98.68

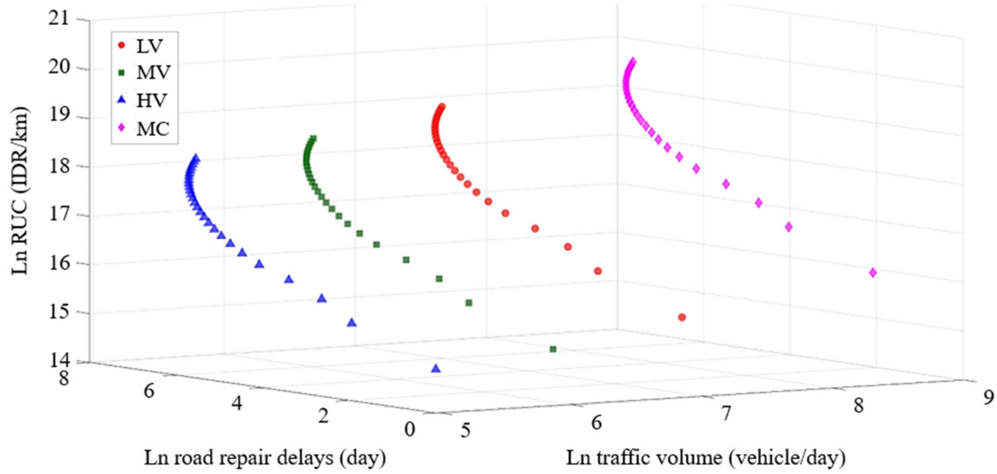
3.5. Development of RUC estimation model by traffic volume and road repair delay

Many studies utilize traffic volume and travel speed as independent variables in developing RUC estimation models. Both variables are very commonly used especially traffic volume. However, there is a novelty in using the RUC estimation model in this study, which includes a road repair delay variable. This variable is important because it significantly impacts the costs incurred due to road repair delays. Unfortunately, awareness of the importance of this variable is often lacking, both among road users and related agencies. Fig. 7 shows the relationship between increasing RUC, increasing traffic volume, and delays in implementing road repairs.

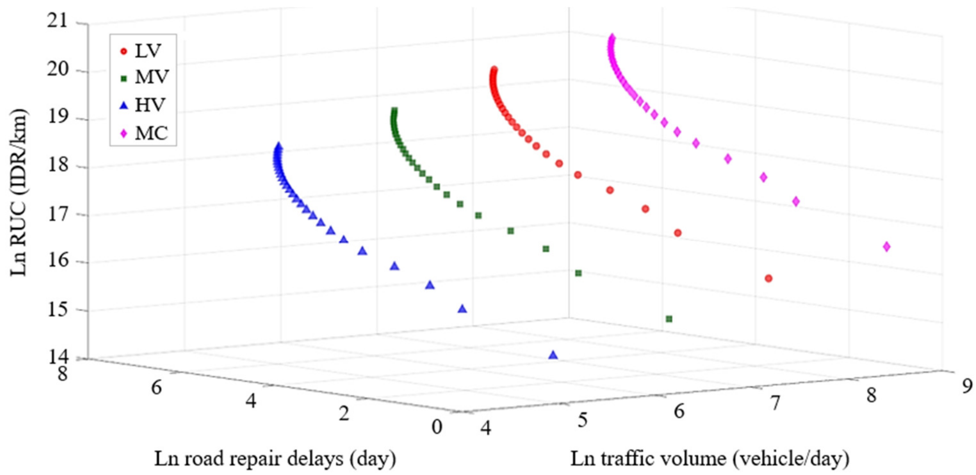
Although the length of road damage is not used as an independent variable in this model due to the potential for multicollinearity with the road repair delay variable, attention to its impact is important. The relationship expressed logarithmically shows the proportional relationship between RUC, traffic volume, and delays in implementing road repairs. Microscopically, the number of RUCs on a section of road will continue to increase along with the growth in vehicle volume. The decision to delay road repairs for longer is also one of the factors that can cause an increase in RUC on a section of road. Thus, the costs arising from delays in road repairs are something new and important to consider because, so far, there has never been a calculation that considers the impact on road users.



(a) Segment 1



(b) Segment 2



(c) Segment 3

Fig. 7 RUC relationship with traffic volume and road repair delays

The formation of the model is based on a simulation where delays in implementing road repairs every month cause an increase in the length of road damage by 0.01 meters, accompanied by an increase in traffic volume. Initial statistical tests in normality, heteroscedasticity, and multicollinearity were carried out to ensure that the model built met the criteria for the best-unbiased estimator. The model was built using logarithmic multiple regression, where the following equation expresses the regression results.

$$\ln\left(\mathrm{RUC}_i\right) = a_i + b_i \times \ln\left(V_i\right) + c_i \times \ln\left(T_i\right) \tag{16}$$

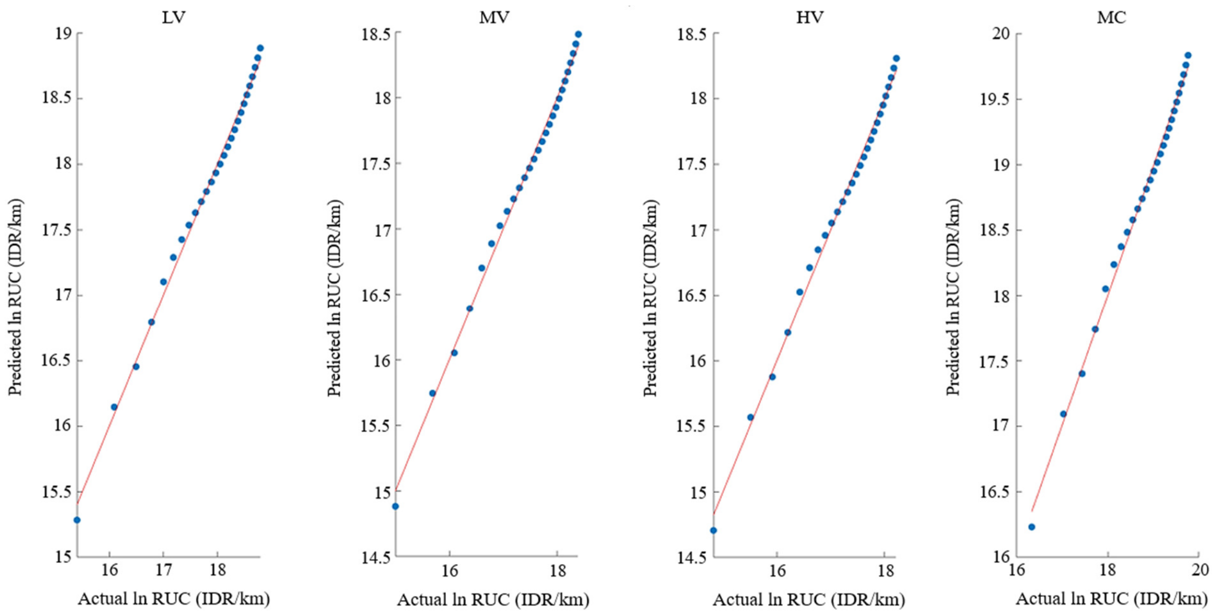
where V_i is the traffic volume for the type of vehicle i (vehicles/day) and T_i is the duration of road repair delays (days). Meanwhile a_i, b_i, and c_i are regression coefficients for vehicle types whose magnitudes are stated in Table 7.

Table 7 RUC estimation model parameters

Vehicle type	Min. traffic volume	Model parameter			Vehicle type	Min. traffic volume	Model parameter		
		a	b	c			a	b	c
LV	650	2.106	2.034	0.442	MV	280	3.404	2.033	0.442
	950	1.595	2.034	0.442		350	3.116	2.033	0.442
	1320	1.505	2.034	0.442		470	2.941	2.033	0.442
HV	120	4.884	2.033	0.442	MC	3670	–0.469	2.034	0.442
	140	4.675	2.033	0.442		4060	–0.707	2.035	0.442
	140	4.834	2.033	0.442		4520	–0.539	2.034	0.442

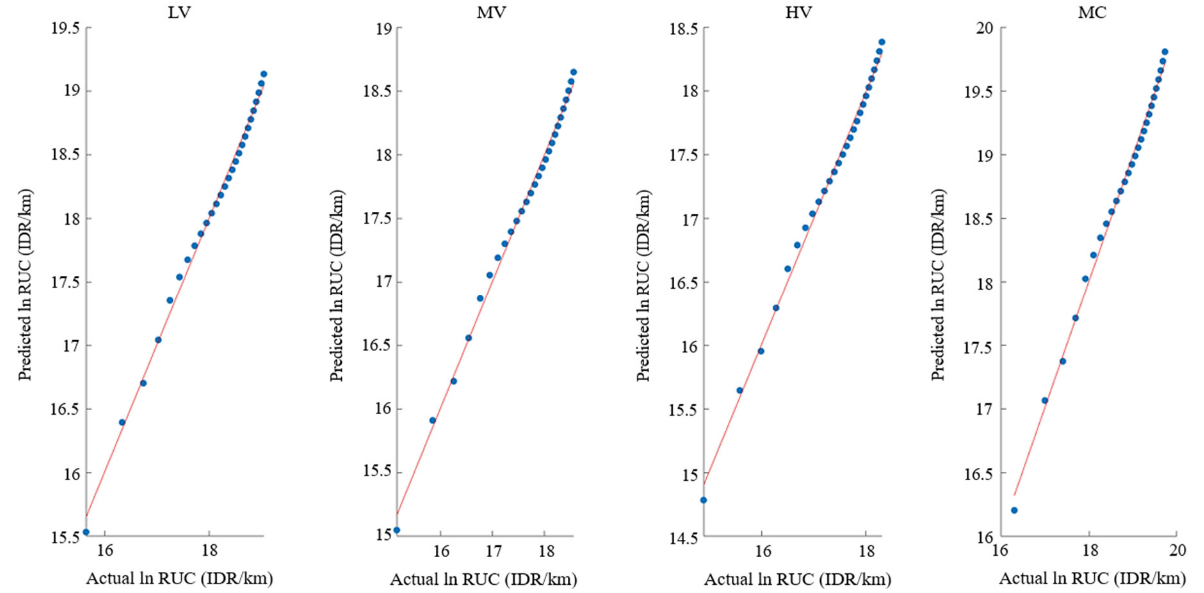
Through the t-test and f-test, the variables traffic volume and repair delay duration individually or in combination significantly influence RUC, as indicated by the value significance of less than 5%. The estimation model was built based on phenomena that occurred at the research location, so there is a possibility that this model will be less accurate when applied to different location characteristics. However, this model is easy to use because the data used is easy to obtain through simple surveys, and this model can provide reasonably accurate RUC estimates considering available constraints. In this study, the level of damage was not included as a variable because the three locations had the same level of damage. In the future, variations in the level of road damage can be used as a variable to see how much influence it has on the amount of RUC. Additionally, scenarios such as differences in the number of lanes may be applicable in future research.

3.6. Validation of RUC estimation model

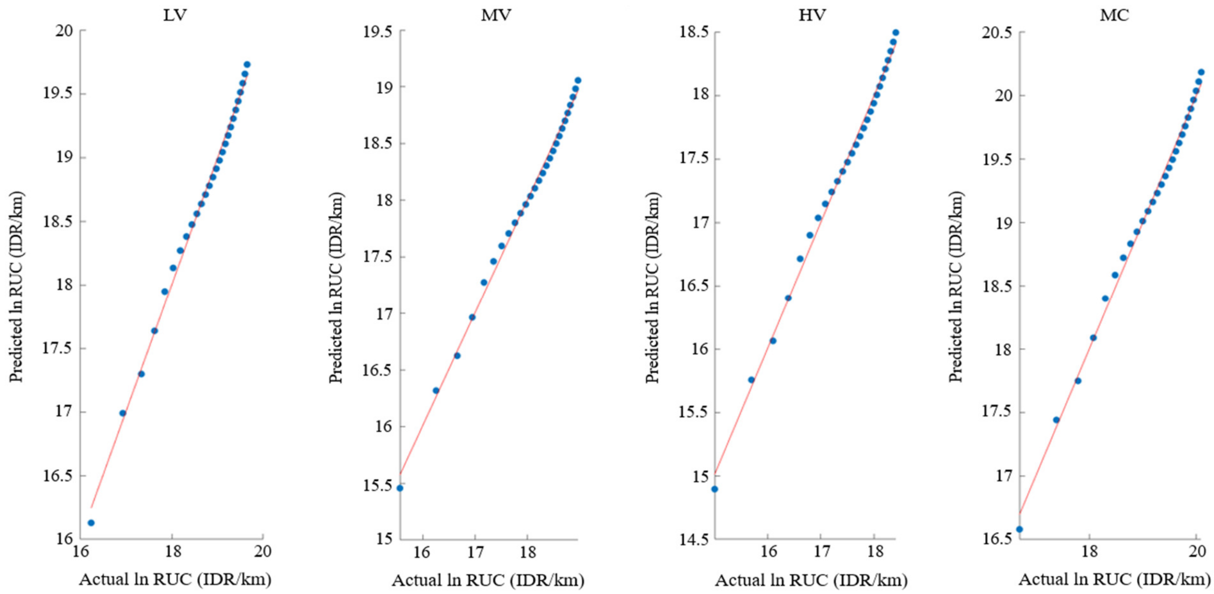


(a) Segment 1

Fig. 8 RUC estimation model and the PTRUC model conclusions



(b) Segment 2



(c) Segment 3

Fig. 8 RUC estimation model and the PTRUC model conclusions (continued)

Model validation was carried out by comparing the RUC calculated using the PTRUC method with the RUC computed using the previously developed estimation model. Fig. 8 shows model validation results for all road conditions and vehicle types. These results indicate a concentration of data on the regression line, which strongly correlates the two methods with a coefficient of determination (R^2) exceeding 90%. This correlation shows that the calculation results between the two methods produce similar RUC values.

3.7. Sensitivity of road user and agency costs due to traffic volume

Sensitivity analysis in this study was used to measure the significance of various factors on RUC and road repair costs borne by the agency. Fig. 9 shows the sensitivity results of the impact of increasing and decreasing traffic volumes (–20%, –10%, 0%, +10%, and +20%) on RUC and agency costs in the form of road repairs while keeping other parameters constant. In this figure, RUC tends to be very sensitive to traffic changes. As traffic volume increases, the opportunity for queues to form increases and can increase speed reductions, which directly impacts increasing travel time. Traffic impacts increase the two components that make up the RUC. On the other hand, repair costs are relatively fixed as traffic volume increases or decreases.

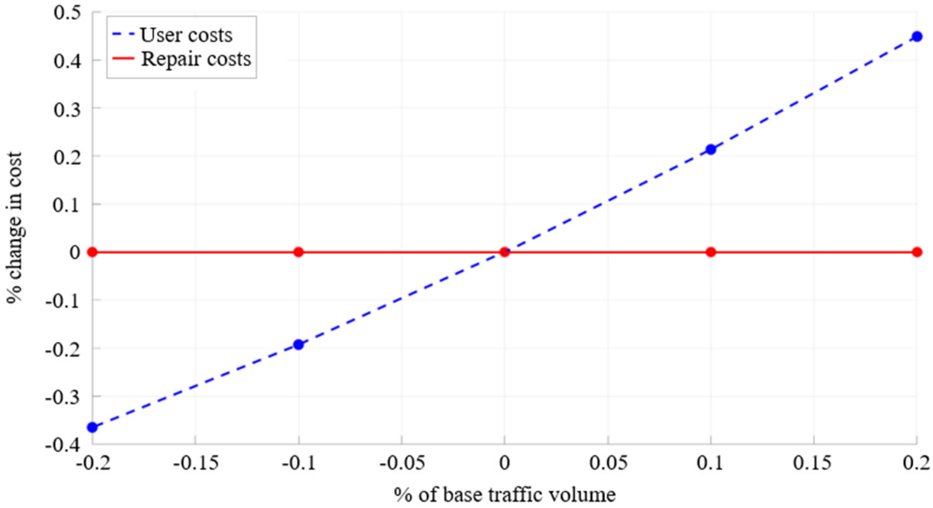
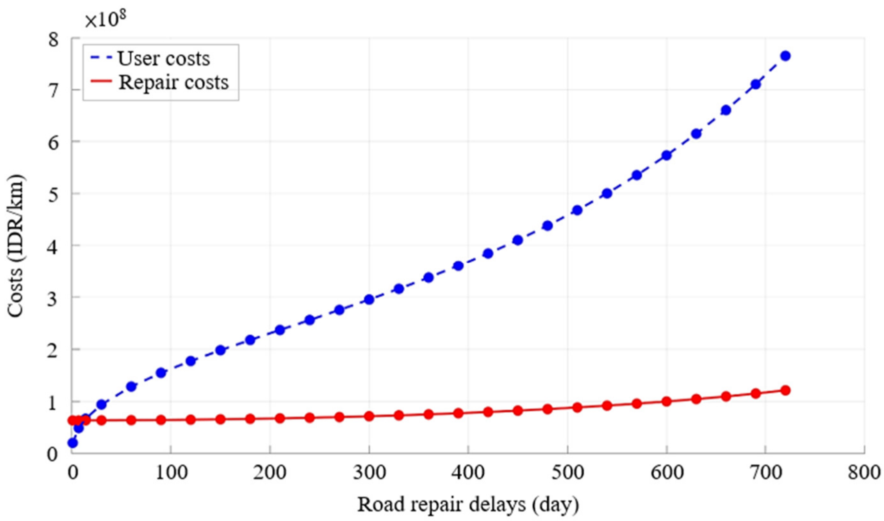


Fig. 9 Sensitivity of user and agency costs to traffic volume

3.8. Changes in road user and agency costs due to repair delays

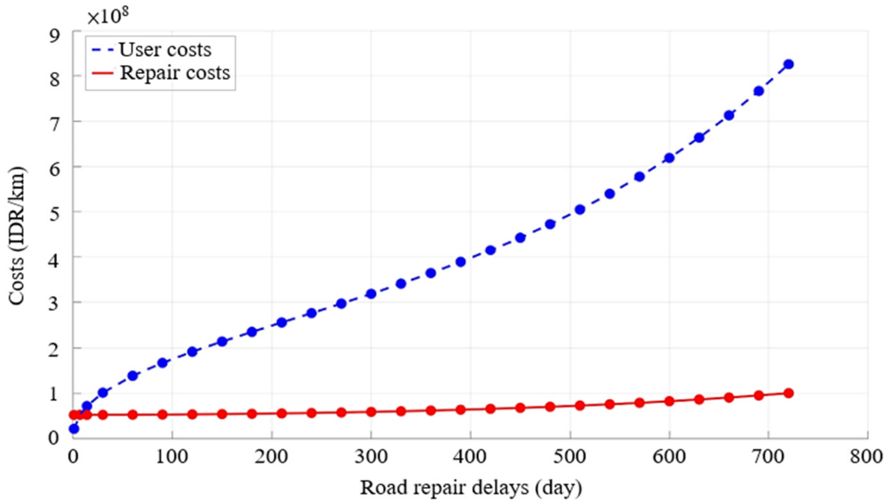
This research reveals studies related to the costs that road users and agencies must bear due to delays in road repairs in the three research locations. In Fig. 10, a significant gap can be seen, indicating that RUC experiences a susceptible increase compared to repair costs as road repairs are delayed longer. In particular, there was an increase of 8.5% per day in delays in handling road repairs for road users, while the agency responsible for this increased by 0.75% per day. This disparity underscores road users' disproportionate burden in the face of repair delays. For a short period, the repair costs borne by the agency are higher than those borne by road users. Over an extended period, significant upgrade differences cause user costs to skyrocket beyond the repair costs.

The results of this study emphasize that it is necessary to take a holistic approach in determining road repair priorities, which takes into account the significant impact on road users, in addition to traditional repair considerations. Compared to the existing literature, this study stands out for its explicit focus on quantifying the relative magnitudes of user costs and agency costs, thereby advocating a paradigm shift toward a more inclusive and equitable improvement decision-making framework. As a result, the implications are enormous, urging policymakers and transportation authorities to recalibrate existing strategies to prioritize timely repairs, reduce cost escalation, and reduce user inconvenience. Future research could explore broader economic implications, alternative repair scheduling approaches, and the long-term effectiveness of proactive maintenance strategies in improving overall road network resilience and user satisfaction.

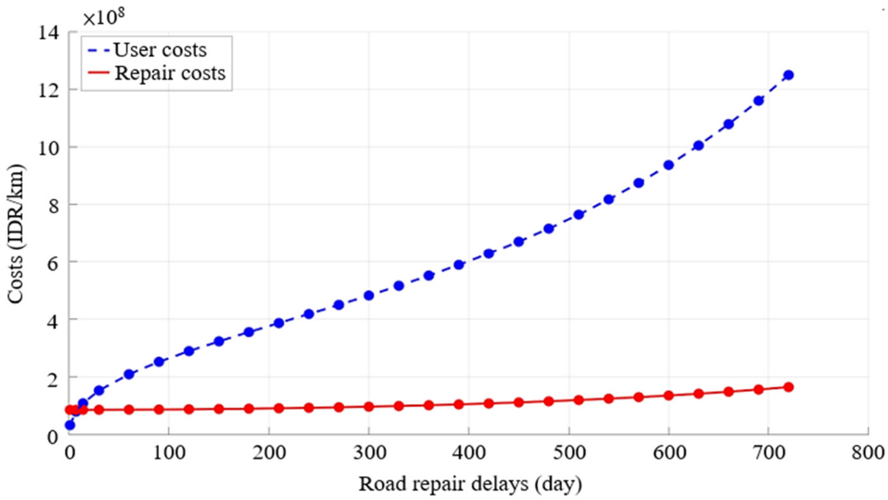


(a) Segment 1

Fig. 10 Impact of repair delays on user costs and agency costs



(b) Segment 2



(c) Segment 3

Fig. 10 Impact of repair delays on user costs and agency costs (continued)

4. Conclusions

This research focuses on analyzing the various negative impacts of road damage experienced by road users and agencies. Its primary aim is twofold: first, to assess the negative consequences of road damage on travel conditions, and second, to devise a model capable of estimating the resulting RUC stemming from increased traffic volume and delays in road repairs. The findings of this study are as follows:

(1) Road damage, varying in length, substantially reduces vehicle speed, leading to increased travel times and subsequently higher RUC. Longer stretches of damage correlate with more significant decreases in speed.

(2) Reduced speeds due to road damage create conditions conducive to vehicle queues, with the length of queues influenced by both the extent of road damage and traffic volume.

(3) Road damage escalates RUC significantly across different vehicle types, with increases ranging from 47% to 99% depending on the vehicle category.

(4) The developed RUC model proves accurate in estimating costs, offering a user-friendly approach that requires minimal data input. Its implementation could enhance awareness of economic losses incurred from neglecting timely road repairs.

(5) Sensitivity tests demonstrate that RUC is highly responsive to traffic volume, suggesting that repairing roads during low-traffic periods could mitigate losses.

(6) Road repair delays exacerbate RUC, often surpassing repair costs. Prompt corrective measures are therefore recommended to minimize losses for all parties involved.

The study acknowledges its limitation in only considering the length of road damage without accounting for variations in damage severity. Future research could address this by incorporating damage severity as a variable, thereby enhancing the accuracy of RUC estimation models and providing a more comprehensive understanding of road damage impacts.

Conflicts of Interest

The authors declare no conflict of interest.

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