

The Impact of Overloaded Trucks on Congestion Costs in Urban Freeways: A Microsimulation Approach Using Weight-in-Motion Data

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ABSTRACT:

Overloaded freight vehicles are widely recognized for accelerating pavement deterioration; however, their operational impacts on traffic performance and congestion costs remain insufficiently quantified. This study proposes an integrated framework combining Weight-in-Motion (WIM) data and microscopic traffic simulation to estimate congestion costs generated by overloaded trucks on urban freeways. Primary WIM data were collected for three truck categories based on the Indonesian toll road classification system, including vehicle weight, overload percentage, and operating speed. Pearson correlation and linear regression analyses were performed to develop overload–speed relationships, which were subsequently implemented in a PTV VISSIM model of a three-lane freeway under five volume-to-capacity (V/C) ratio scenarios ranging from 0.2 to 1.0. Congestion costs were estimated using travel time delay and the Indonesian Value of Time (VOT) parameter. The results indicate a strong inverse relationship between overload percentage and truck operating speed, with correlation coefficients ranging from -0.889 to -0.953 . Simulation results demonstrate that congestion costs increase nonlinearly with both overload severity and traffic density, with Type 3 trucks generating the highest congestion cost of IDR 46,641/km under saturated traffic conditions. The findings reveal that overloaded trucks impose substantial operational externalities beyond pavement deterioration and highlight the importance of incorporating congestion impacts into freight enforcement and transportation policy evaluation. By integrating empirical WIM observations with traffic microsimulation, this study provides a practical approach for quantifying the economic consequences of overloaded freight operations and supporting evidence-based transport management strategies.

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1. Introduction

Freight transportation plays a vital role in supporting economic activities and logistics

distribution systems. However, overloaded truck operations remain a persistent challenge in many developing countries, including Indonesia.

Excessive vehicle loading has been widely associated with accelerated pavement deterioration, increased maintenance expenditures, and reduced roadway service life (Nariendra & Juanita, 2023; Jacob & Feypell, 2010). Consequently, most freight enforcement policies have primarily focused on mitigating infrastructure damage through vehicle weight regulations and overload control measures.

In addition to infrastructure deterioration, overloaded trucks can significantly affect traffic operations. Heavy vehicles generally exhibit lower acceleration capability, reduced maneuverability, and lower operating speeds than passenger vehicles, resulting in disturbances to traffic flow and reductions in roadway capacity (Santos et al., 2021). Under congested conditions, slow-moving freight vehicles may create moving bottlenecks and traffic shockwaves that increase travel time and reduce operational efficiency on urban freeways (Li & Wang, 2020). Furthermore, overloaded trucks tend to amplify these effects because excessive loading further degrades vehicle performance and operating speed (Wang et al., 2021; Zhang et al., 2022).

Recent studies have investigated the influence of heavy vehicles on freeway performance using traffic simulation approaches. Cui et al. (2021) reported that slow-moving freight vehicles can reduce traffic speed and increase travel time variability, particularly under high-density traffic conditions. Similarly, Rahman et al. (2021) demonstrated that a relatively small proportion of heavy vehicles may significantly affect multilane freeway performance when traffic demand approaches roadway capacity. Despite these findings, most existing studies focus either on pavement impacts or traffic flow performance, while limited attention has been given to the economic consequences of operational disruptions caused by overloaded freight vehicles.

Advances in Weight-in-Motion (WIM) technology provide opportunities to continuously monitor vehicle weight and operational characteristics under real traffic conditions without interrupting traffic flow (Jacob & Feypell, 2010). At the same time,

microscopic traffic simulation platforms such as PTV VISSIM enable detailed representation of vehicle interactions, lane-changing behavior, and traffic dynamics (Fellendorf & Vortisch, 2010). Although these approaches have been widely applied independently, studies integrating empirical WIM observations with microscopic traffic simulation to quantify congestion costs generated by overloaded trucks remain limited. Consequently, the operational externalities associated with overloaded freight vehicles are often underestimated in transport policy evaluation and freight enforcement strategies.

To address this research gap, this study develops an integrated framework combining WIM-based overload analysis and PTV VISSIM microsimulation to estimate congestion costs generated by overloaded truck operations on urban freeways. The study first establishes overload–speed relationships for different truck categories using empirical WIM data and subsequently implements the resulting models in a microscopic traffic simulation environment under various traffic demand scenarios. Congestion costs are then estimated based on travel time delays using the Indonesian Value of Time (VOT) framework (Kementerian Perhubungan Republik Indonesia, 2023). The primary contribution of this study is the quantification of operational externalities caused by overloaded freight vehicles beyond conventional pavement damage assessment, providing evidence to support freight enforcement policies, congestion management strategies, and transportation economic evaluations.

2. Literature Review

Overloading of freight vehicles has long been recognized as a major transportation issue because it generates adverse impacts on infrastructure, traffic operations, and road safety. Most previous studies have focused on pavement deterioration resulting from excessive axle loads, demonstrating that overloaded trucks accelerate pavement damage, increase maintenance requirements, and reduce roadway service life (Jacob & Feypell, 2010; Nariendra & Juanita,

2023). Consequently, vehicle weight regulations and overload enforcement programs have primarily been developed to mitigate infrastructure-related impacts.

In addition to pavement deterioration, heavy vehicles significantly influence traffic flow characteristics due to their lower acceleration capability, reduced maneuverability, and slower operating speeds compared with passenger vehicles. Cui et al. (2021) reported that heavy vehicles can reduce average traffic speed and increase travel time variability, particularly under congested traffic conditions. Similarly, Li and Wang (2020) demonstrated that slow-moving trucks may create moving bottlenecks and traffic shockwaves that reduce roadway capacity and operational efficiency. These impacts become more pronounced as traffic demand approaches roadway capacity, where overtaking opportunities become increasingly limited (Rahman et al., 2021). Furthermore, overloaded trucks may intensify these operational disturbances because excessive loading further reduces vehicle performance and operating speed (Wang et al., 2021; Zhang et al., 2022).

Weight-in-Motion (WIM) technology provides an effective approach for continuously measuring vehicle weight and operational characteristics under actual traffic conditions. Unlike conventional static weighing systems, WIM enables dynamic monitoring without disrupting traffic flow and has therefore been widely applied for freight monitoring, overload enforcement, and pavement management purposes (Jacob & Feypell, 2010). Recent studies have shown that WIM data can also be utilized to investigate the relationship between vehicle loading conditions and operational performance, including vehicle speed and traffic flow behavior (Wang et al., 2021).

Congestion cost represents the economic value of delays experienced by road users due to reduced traffic performance. According to Litman (2023), congestion costs may include travel time losses, vehicle operating costs, fuel consumption, environmental impacts, and productivity losses. While previous studies have

investigated the operational effects of heavy vehicles and overloaded trucks, limited research has integrated empirical WIM observations with microscopic traffic simulation to quantify congestion costs generated by overloaded freight vehicles. This study addresses this gap by combining WIM-based overload-speed analysis and PTV VISSIM microsimulation to estimate the congestion externalities associated with overloaded truck operations on urban freeways.

3. Methodology

3.1 Research Framework

This study integrates empirical Weight-in-Motion (WIM) observations with microscopic traffic simulation to estimate congestion costs generated by overloaded truck operations. The methodology consists of four stages: (1) collection of WIM data for freight vehicles, (2) statistical analysis to establish overload-speed relationships, (3) development of overload-speed scenarios, and (4) traffic microsimulation and congestion cost estimation. Figure X illustrates the overall research framework.

3.2 Study Area and Data Collection

Primary data were obtained from a Weight-in-Motion (WIM) station located on an urban toll road in Indonesia. The WIM system continuously records vehicle weight and operational characteristics without interrupting traffic flow. The collected dataset included vehicle classification, permissible gross vehicle weight, actual gross vehicle weight, overload percentage, and operating speed.

The analysis focused on three truck categories based on the Indonesian toll road classification system: Type 1 Truck, Type 2 Truck, and Type 3 Truck. A total of 277 truck observations were collected, consisting of 25 Type 1 Trucks, 209 Type 2 Trucks, and 43 Type 3 Trucks. Data screening was performed to remove incomplete and inconsistent observations prior to statistical analysis.

The overload percentage was calculated using Equation (1).

$$P = (W_a - W_p) / W_p \quad (1)$$

where:

P = overload percentage

W_a = actual vehicle weight (kg)

W_p = permissible vehicle weight (kg)

Table 1 WIM Dataset Summary

Vehicle Category	Number of Samples	Percentage (%)
Type 1 Truck	25	9.0
Type 2 Truck	209	75.5
Type 3 Truck	43	15.5
Total	277	100.0

3.3 Correlation and Regression Analysis

Pearson correlation analysis was conducted to evaluate the relationship between overload percentage and truck operating speed. Subsequently, linear regression models were developed to estimate the effect of overload percentage on truck operating speed.

The general regression model is expressed as Equation (2).

$$V = a + bP \quad (2)$$

where:

V = truck operating speed (km/h)

P = overload percentage

a = regression constant

b = regression coefficient

The regression results are summarized in Table 2.

Table 2 Correlation and Regression Results

Vehicle Category	Correlation Coefficient (r)	Regression Equation	R ²
Type 1 Truck	-0.889	V = 75.436 - 28.694P	0.790
Type 2 Truck	-0.939	V = 75.227 - 39.476P	0.882
Type 3 Truck	-0.953	V = 75.903 - 51.733P	0.908

All models exhibited strong negative correlations between overload percentage and operating speed, indicating that increasing overload levels substantially reduce truck operating speed.

3.4 Overload-Speed Scenario Development

Based on the regression models, eleven overload scenarios ranging from 0% to 100% overload at 10% increments were generated. The estimated truck speeds obtained from the regression equations were subsequently used as input parameters in the microsimulation model.

Table 3 Speed Scenarios Based on Overload Percentage

Overload (%)	Type 1 (km/h)	Type 2 (km/h)	Type 3 (km/h)
0	75	75	75
10	72	71	70
20	69	67	65
30	66	63	60
40	63	59	55
50	61	55	50
60	58	51	44
70	55	47	39
80	52	43	34
90	49	39	29

Overload (%)	Type 1 (km/h)	Type 2 (km/h)	Type 3 (km/h)
100	46	35	24

3.5 Traffic Microsimulation Model

Traffic operations were simulated using PTV VISSIM on a 1-km three-lane freeway segment with an assumed capacity of 7,500 passenger car units per hour (pcu/h). Passenger vehicle desired speed was maintained at 75 km/h, while truck speeds varied according to the overload-speed scenarios.

Five traffic demand conditions were evaluated using V/C ratios of 0.2, 0.4, 0.6, 0.8, and 1.0. To isolate the operational impact of overloaded freight vehicles, one truck with specific overload characteristics was introduced into the traffic stream under each scenario.

Table 4 Traffic Demand Scenarios

V/C Ratio	Traffic Volume (pcu/h)
0.2	1,500
0.4	3,000
0.6	4,500
0.8	6,000
1.0	7,500

Table 5 Key VISSIM Simulation Parameters

Parameter	Value
Road Length	1 km
Number of Lanes	3
Capacity	7,500 pcu/h
Passenger Vehicle Speed	75 km/h
Truck Speed	Variable
Car-Following Model	Wiedemann 99
Simulation Resolution	10 time steps/s
Simulation Runs	10
Evaluation Period	3,600 s

3.6 Congestion Cost Estimation

Congestion costs were estimated based on travel time delay using the Value of Time (VOT) approach. The congestion cost equation is expressed as Equation (3).

$$CC = \Delta TT \times VOT \times Q \quad (3)$$

where:

CC = congestion cost (IDR/km)

ΔTT = additional travel time caused by overloaded truck operations (hour)

VOT = value of time (IDR/hour)

Q = traffic flow (veh/hour)

The Value of Time (VOT) was adopted from JUTPI 3 issued by the Indonesian Ministry of Transportation, with a value of IDR 11,000/hour.

The estimated congestion cost represents travel time delay cost only and excludes vehicle operating costs, fuel consumption, emissions, accident costs, and other externalities. These limitations are considered in the discussion section.

4. Results

4.1 Correlation and Regression Analysis

The relationship between overload percentage and truck operating speed was evaluated using Pearson correlation and linear regression analyses. As presented in Table 2, all truck categories exhibited strong negative correlations, with correlation coefficients ranging from -0.889 to -0.953. These results indicate that increasing overload levels consistently reduce truck operating speed.

The developed regression models also demonstrated strong explanatory power, with coefficients of determination (R^2) ranging from 0.790 to 0.908. Type 3 Trucks exhibited the strongest relationship between overload percentage and operating speed, indicating that heavier freight vehicles are more sensitive to excessive loading conditions. The regression results further show that the rate of speed reduction increases with truck category, with Type 3 Trucks experiencing the greatest decline in operating speed for a given increase in overload percentage.

Based on the developed regression equations, overload-speed scenarios were generated for overload levels ranging from 0% to 100%. The results indicate that truck operating speed decreases substantially as overload percentage increases. Under the maximum overload condition, operating speed decreased from approximately 75 km/h to 46 km/h, 35 km/h, and 24 km/h for Type 1, Type 2, and Type 3 Trucks, respectively.

4.2 Microsimulation Results

The overload-speed scenarios were subsequently implemented in the PTV VISSIM microsimulation model under five traffic demand conditions represented by V/C ratios of 0.2, 0.4, 0.6, 0.8, and 1.0. The objective was to evaluate the operational impacts generated by overloaded trucks under varying levels of traffic congestion.

Simulation results revealed that overloaded trucks generated relatively minor disturbances under low traffic demand conditions because surrounding vehicles were able to perform overtaking maneuvers with limited operational disruption. However, as traffic demand increased, the impacts became progressively more significant.

Under moderate traffic conditions ($V/C = 0.6$), reductions in truck operating speed began to affect average traffic performance, resulting in

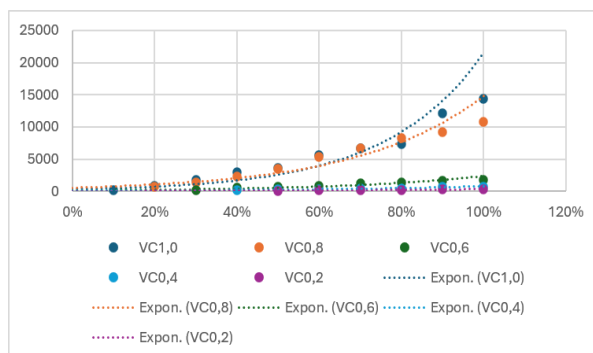
measurable increases in travel time and delay. Under congested and saturated traffic conditions ($V/C = 0.8$ and 1.0), overloaded trucks acted as moving bottlenecks that reduced traffic efficiency and generated substantial delays for surrounding vehicles.

The magnitude of these operational impacts was strongly influenced by truck category. Due to their greater speed reductions under overloaded conditions, Type 3 Trucks consistently generated the largest disturbances to traffic flow, followed by Type 2 and Type 1 Trucks. These findings indicate that the operational consequences of overloaded freight vehicles become increasingly severe as traffic demand approaches roadway capacity.

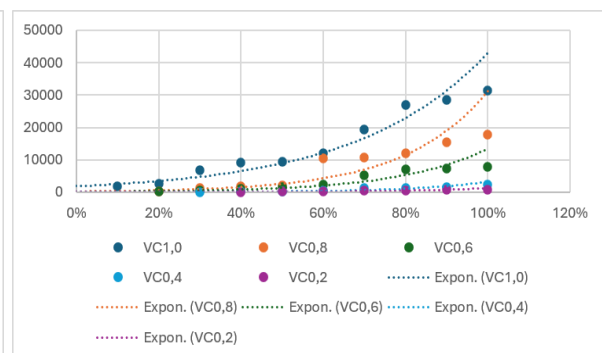
4.3 Congestion Cost Analysis

Congestion costs were estimated using travel time delay and the Indonesian Value of Time (VOT) parameter. The results demonstrate that congestion costs increase significantly with both overload percentage and traffic density.

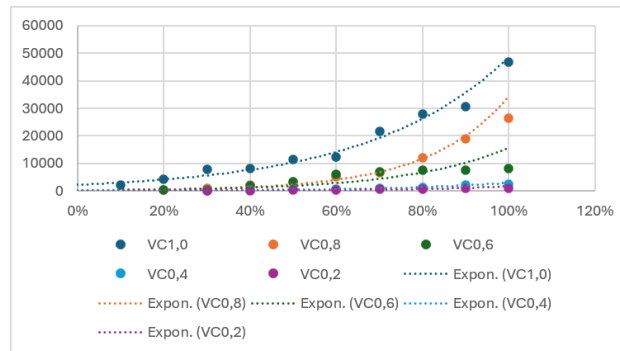
Table 6 presents the maximum congestion costs observed under saturated traffic conditions ($V/C = 1.0$). Type 1 Trucks generated a maximum congestion cost of IDR 14,399/km, while Type 2 and Type 3 Trucks generated substantially higher costs of IDR 31,361/km and IDR 46,641/km, respectively.



Type 1



Type 2



Type 3

Figure 1 Relationship Between Overload Percentage and Truck Operating Speed for Different Truck Categories

Table 6 Maximum Congestion Cost under Saturated Traffic Conditions

Vehicle Category	Maximum Congestion Cost (IDR/km)
Type 1 Truck	14,399
Type 2 Truck	31,361
Type 3 Truck	46,641

Figure 1 shows that congestion costs increase exponentially as overload percentage increases. At lower overload levels, the increase in congestion cost is relatively moderate because truck operating speeds remain sufficiently high to minimize traffic disturbances. However, as overload severity increases, truck operating speeds decrease substantially, resulting in larger delays and rapidly increasing congestion costs.

The exponential trend is particularly evident for Type 2 and Type 3 Trucks. Among all vehicle categories, Type 3 Trucks generated the highest congestion costs across the entire range of overload conditions. Under the maximum overload scenario, the congestion cost generated by a Type 3 Truck reached IDR 46,641/km, approximately 3.2 times higher than that generated by a Type 1 Truck. This finding demonstrates that the economic impacts of overloaded freight vehicles increase disproportionately as both vehicle weight and overload severity increase.

The results are consistent with previous studies that identified heavy vehicles as significant contributors to traffic disturbances and moving bottlenecks under congested traffic conditions (Li & Wang, 2020; Cui et al., 2021; Rahman et al.,

2021). However, unlike previous studies that primarily focused on traffic performance indicators, the present study quantifies the associated economic impacts using empirical overload-speed relationships derived from WIM observations. The findings confirm that overloaded freight vehicles generate substantial operational externalities beyond pavement deterioration and therefore should be considered in freight enforcement policies, congestion pricing strategies, and transportation economic evaluations.

Conclusion

This study developed an integrated framework combining Weight-in-Motion (WIM) observations and microscopic traffic simulation to evaluate the congestion costs generated by overloaded truck operations on urban freeways. The results demonstrated a strong inverse relationship between overload percentage and truck operating speed, with correlation coefficients ranging from -0.889 to -0.953. The developed regression models showed that increasing overload levels substantially reduce truck operating speeds, particularly for heavier vehicle categories.

The microsimulation results revealed that the operational impacts of overloaded trucks are highly dependent on traffic demand conditions. Under low traffic volumes, the resulting disturbances were relatively limited because surrounding vehicles could perform overtaking maneuvers with minimal disruption. However, as traffic demand approached roadway capacity, overloaded trucks acted as moving bottlenecks that reduced traffic efficiency and generated significant travel delays. The estimated congestion costs increased nonlinearly with overload severity, with Type 3 Trucks generating the highest congestion cost of IDR 46,641/km under saturated traffic conditions.

The findings indicate that overloaded freight vehicles impose substantial operational externalities beyond pavement deterioration. While existing overload enforcement policies primarily focus on infrastructure preservation, the results suggest that congestion impacts

should also be considered when evaluating the economic consequences of overloaded truck operations. The proposed methodology provides a practical tool for supporting freight enforcement strategies, congestion management policies, and transportation economic assessments.

This study is subject to several limitations. The analysis was conducted using a single-truck simulation approach to isolate the operational impacts of overloaded vehicles under controlled conditions. Furthermore, the congestion cost estimation was limited to travel time delay costs and did not include vehicle operating costs, fuel consumption, emissions, accident risks, or other externalities. Future research should investigate interactions among multiple freight vehicles, heterogeneous traffic conditions, dynamic traffic assignment, and broader economic and environmental impacts associated with overloaded freight transportation.

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