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The Effect of Weigh in Motion Installation on Traffic Volume, Speed and Accident Rate of Goods Vehicles on The Pekanbaru – Dumai Toll Road

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Abstract: This study aims to analyze the impact of implementing a Weigh In Motion (WIM) system on the traffic performance of freight vehicles on the Pekanbaru-Dumai Toll Road. The WIM was installed in response to the Circular Letter of the Minister of Transportation No. 116 of 2021 and functions as an automated enforcement technology to prevent Over Dimension Over Load (ODOL) vehicles from entering the toll road. The research method used was a one-group pretest-posttest experimental design with a descriptive-comparative quantitative approach. Secondary data was obtained from the toll road operator (PT Hutama Karya), covering three months before (December 2023 - February 2024) and three months after (March 2024 - May 2024) the WIM installation at four main toll gates. Three performance variables were analyzed: total traffic volume, average speed of freight vehicles, and the number of accidents involving freight vehicles. The analysis results show that after the WIM installation, there were changes with substantial practical significance: (1) total traffic volume decreased by 7.08% (from an average of 72,358 to 67,233 vehicles/month), indicating a filtering effect on ODOL vehicles; (2) the average speed of freight vehicles increased by 10.41% (from 29.88 km/h to 32.99 km/h), as an impact of improved traffic stream homogeneity; and (3) the number of freight vehicle accidents dropped sharply by 50% (from 2.67 to 1.33 incidents/month), with a large effect size (Cohen's d) of 1.155. The study concludes that WIM is effective not only as an enforcement tool but also as a traffic management instrument that creates a beneficial trade-off: a limited reduction in volume is exchanged for increased efficiency and, most importantly, a highly significant improvement in safety. This research recommends the expansion of WIM to other strategic toll road sections and further studies with longer observation periods and quasi-experimental designs.

Keywords: Weigh In Motion, ODOL, Traffic Volume, Speed, Accident Rate, Automated Enforcement, Toll Road.

INTRODUCTION

The increasing volume of freight vehicle traffic in industry is vital to the production and distribution process. Transportation plays a crucial role in industry, from moving raw materials and optimizing production processes to distributing finished products to consumers. Problems arising from freight transportation include vehicles stopping at random locations, overloading, and environmental issues related to noise, vibration, and exhaust fumes.(Arwini et al., 2023).Traffic volume is a measure of the amount of traffic flow. Traffic volume indicates the number of vehicles passing a point of observation in a unit of time.(Silvia Sukirman, 1999)**.**In the world of transportation, we are familiar with the term Over Dimension Over Load (ODOL) vehicles. As the name suggests, these vehicles have excessive dimensions and/or loads, violating vehicle dimension and carrying capacity regulations. At first glance, overloaded vehicles appear to only disrupt traffic flow. However, these vehicles also cause road damage because the load they carry exceeds the pavement's design capacity, accelerating the road's deterioration process.(Rezky Yosita, 2021).

One of the causes of accidents on toll roads is the significant speed disparity between vehicles, especially when trucks traveling on the toll road are carrying over-dimension-over-load (ODOL) trucks at low speeds due to excessive loads. This speed disparity often leads to rear-end collisions.(Masya Famely, 2023)Speed is a quantity that indicates the distance traveled by a vehicle divided by the travel time. It is usually expressed in km/h. This speed describes the vehicle's motion. Good road planning must of course be based on the selected speed and the assurance that it is appropriate for the road's conditions and intended function.(Silvia Sukirman, 1999).

The Pekanbaru-Dumai Toll Road is part of the Trans-Sumatra Toll Road, connecting Pekanbaru and Dumai, with a length of 131 kilometers. This toll road serves as the main route from Pekanbaru, the provincial capital, to Dumai, the port city. Furthermore, the Pekanbaru-Dumai Toll Road also connects Pekanbaru to North Sumatra Province. Therefore, this route is a major economic route frequently used by freight vehicles, some of which are classified as heavy-duty (ODOL) vehicles.(Ministry of Public Works and Public Housing, 2020).

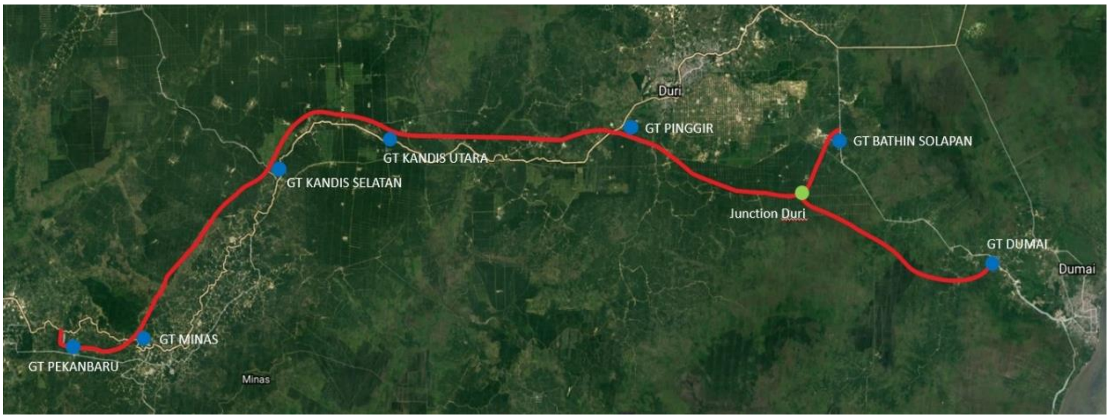

Figure1. Pekanbaru - Dumai Toll Road Route

To maintain road infrastructure from being damaged more quickly and reduce the level of traffic accidents, PT. Hutama Karya (Persero) as the Toll Road Business Entity (BUJT) of the Pekanbaru - Dumai Toll Road Section will install Weigh In Motion in December 2023 - February 2024, so that goods vehicles that fall into the ODOL category will be prevented from entering the toll road by being turned around to exit the toll road access.

The locations where Weigh In Motion will be installed are locations that are frequently passed by goods vehicles on the Pekanbaru - Dumai Toll Road, namely the first Pekanbaru

Toll Gate Entrance Access Road is the access road to the toll road from Pekanbaru City, second Minas Toll Gate Entrance Access Road is the access road to the toll road from Siak Regency, next Pinggir Toll Gate Entrance Access Road is the access road to the toll road from Duri City and Bathin Solapan Toll Gate Entrance Access Road is the access road to the toll road from the direction of North Sumatra Province.

The installation of Weigh In Motion on Toll Roads is in line with the Minister of Transportation's Circular Letter Number 116 of 2021 concerning Supervision and Enforcement of Goods Transport Vehicles for Over Dimension Violations and Over Loading Violations on Toll Roads.This is a response to a growing problem in the transportation system. The phenomenon of goods vehicles exceeding their permitted dimensions or loads (ODOL) has become a serious concern due to the potential for infrastructure damage, the risk of accidents, and disruption to traffic flow. To address this issue, installing Weigh-In-Motion on toll roads is not only a practical solution but also a proactive step in implementing applicable regulations.

In line with the aforementioned Circular Letter from the Minister of Transportation, the installation of Weigh-In-Motion (WIM) on toll roads not only serves as a detection tool but can also be used as an enforcement instrument. This technology provides accurate data on goods vehicles violating regulations and facilitates enforcement in accordance with applicable regulations. However, policy implementation requires evidence-based evaluation. Although the regulatory basis and technical justification for WIM installation are strong, empirical evidence regarding its operational impact, especially in the Indonesian context, remains limited. Most previous studies have focused on aspects of technological accuracy, potential benefits, or general impact analysis of ODOL (Septiana & Zaini, 2018; Syarif & Prasetia, 2019). Research specifically measuring and analyzing changes in transportation system performance variables, such as volume, speed, and accident rates, as a direct result of WIM implementation on a specific road section, is still rare.

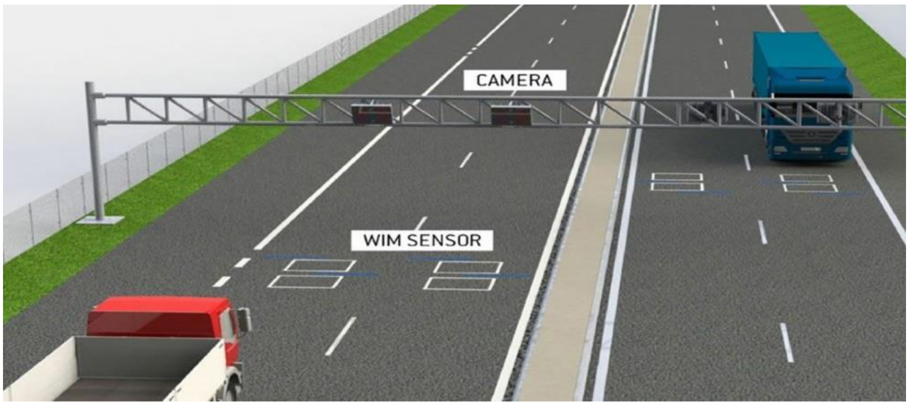

Figure 2. Illustration of Weigh In Motion Installation on Toll Road

A comprehensive evaluation of the impact of Weigh-in-Motion installation is essential, including an analysis of changes in traffic volume, speed, and accident rates for freight vehicles before and after implementation. This data will serve as the basis for assessing the effectiveness of Weigh-in-Motion technology as a tool for detecting violations by freight vehicles.

Beyond being a detection and enforcement tool, the Weigh-In-Motion installation can also be used as a valuable data analysis tool. Data collected from this device can be used to understand violation trends, traffic patterns, and accident risk trends on toll roads. This information can form the basis for developing more effective policies in the future to improve safety, reduce losses due to violations, and improve the overall transportation system.

Based on the complexity of the ODOL problem and the urgency of post-implementation evaluation of the policy, this study was conducted to analyze the effect of Weigh In Motion (WIM) installation on traffic volume, speed and accident rate of goods vehicles on the Pekanbaru-Dumai Toll Road. This case study is designed as an empirical evaluation that compares conditions before and after the implementation of WIM, in order to provide quantitative evidence regarding the effectiveness of this technology not only as a law enforcement tool, but also as an instrument in improving traffic safety and smoothness (safety and traffic flow improvement instrument).

METHOD

Operationalization of variables is a critical stage in quantitative research, transforming conceptual variables (constructs) into measurable variables. This process aims to define boundaries, identify indicators, determine measurement scales, and formulate appropriate data collection techniques and instruments for each variable studied. Without clear and structured operationalization, measurements become ambiguous, the resulting data becomes unreliable, and hypothesis testing loses its validity.

This study used a quasi-experimental design with a one-group pretest–posttest design. This design was chosen because the intervention (WIM installation) was applied at all sample locations, thus precluding the formation of a true control group.

The population in this study is defined as all recorded occurrences of freight vehicle passages entering each toll gate (access point) along the Pekanbaru-Dumai Toll Road during the time period specified in the study. Therefore, the unit of analysis is the freight vehicle passage records, not the physical vehicles themselves.

The sample for this study was taken using a purposive sampling technique based on location criteria. The sample was determined by selecting 4 (four) of the total 7 (seven) toll gate entrances on the toll road. The four selected locations are where PT. Hutama Karya (Persero) will install the Weigh In Motion (WIM) system, as well as the toll gates with the highest freight vehicle crossing intensity based on historical traffic data. Thus, this sample is considered representative of the main freight vehicle movement patterns on the toll road. The four sample locations are:

1. Pekanbaru Toll Gate Entry Access
2. Minas Toll Gate Entry Access
3. Pinggir Toll Gate Entry Access
4. Bathin Solapan Toll Gate Entry Access

The selection of samples at these four locations allows the study to observe the impact of the intervention (installation of WIM) at the most significant strategic points on the overall volume and behavior of goods vehicles.

This study aims to analyze the effect of the installation of a Weigh-In-Motion (WIM) system on three variables: traffic volume, average speed, and freight vehicle accident rate on the Pekanbaru-Dumai toll road. Based on the specific characteristics of the data to be analyzed, this study adopts Descriptive-Comparative Analysis as the primary analytical method, with in-depth methodological considerations.

1. Data Characteristics and Their Implications for Method Selection

   The data analyzed in this study have two key characteristics that determine the choice of analysis technique:

   a. The Nature of Data as a Selected Time Population

      The data represents a complete record (population) of three monthly periods before and three monthly periods after the installation of the WIM at a specific location. This data is not a random sample drawn from a broader time population.

   b. Very Limited Number of Observation Units (N=3)

The unit of analysis is the monthly period, with only three data pairs (before-after) available. These two characteristics have serious methodological implications for the suitability of conventional inferential statistical methods:

1) Paired Sample t-TestSuboptimal
   For data with N=3, this parametric test will have statistical power close to zero (df = 2). This condition makes the risk of Type II Error (failure to detect a significant effect) very high. In other words, this test will mathematically almost certainly result in a "not significant" conclusion regardless of the magnitude of the actual observed change, making the statistical decision uninformative and potentially misleading.
2) Inference Goal Mismatch
   Inferential tests such as the t-test aim to generalize sample results to the population. Because the data already represent the population of the selected period, this generalization goal becomes irrelevant.

2. Descriptive-Comparative Analysis as the Right and Robust Choice
   Based on the above considerations, Descriptive-Comparative Analysis was chosen as the core method due to its greater suitability:
   a. Focus on Effect Size and Practical Significance
      This method allows a focus on the real magnitude of change (in absolute and percentage terms) and the consistency of trends, which are more meaningful for evaluating the impact of a policy than mere statistical significance.
   b. Transparency and Accessibility
      The descriptive and comparative presentation of results (through tables, graphs and percentages) makes the findings accessible and understandable to a wide range of stakeholders, from academics to practitioners.
   c. Conformity to Pretest-Posttest Design
      This method is inherently designed to describe and compare conditions before and after an intervention, which is in line with the research design.
3. Integrated Analysis Procedures (Core and Transparency)
   To ensure transparency, the analysis is performed in two layers:
   a. Core Layer (Descriptive-Comparative Analysis)
      1) Descriptive statistics (mean and standard deviation) for each variable before and after.
      2) Calculation of absolute change (Δ) and percentage ($\%\Delta$).
      3) Analysis of monthly trend consistency (up/down in each of the three months).
      4) Data visualization for clarity.
   b. Transparency Layer (Additional Analysis for Methodological Context)
      As a commitment to full academic transparency, researchers will also present the results of:
      1) Paired Sample t-TestThe presentation of the results of this test, which is predicted to show a high p-value due to low power, will serve as part of the methodological discussion in Chapter IV to concretize and strengthen the scientific justification behind the choice of descriptive-comparative analysis as the primary method.
      2) Effect Size Calculation (Cohen's d). To provide another illustration of the magnitude of the effect that is independent of the size of N.

4. Methodological Conclusion
   Within this framework, research uses not the most common methods, but the most appropriate ones, based on a critical dialogue between research objectives, data characteristics, and statistical principles. Descriptive-Comparative Analysis is positioned not as a second choice, but rather as a first choice that is more informative and valid for the context of this research data.
5. Critical Notes on Statistical Analysis with Limited Data
   This study used three pairs of monthly data (N=3) as the unit of analysis. With this very limited sample size, conventional inferential statistical tests such as the paired sample t-test would have very low statistical power (approaching zero), almost certainly resulting in an "insignificant" conclusion even if there is a significant real-world change. Therefore, this study does not rely on statistical significance (p-value) as the primary basis for drawing conclusions.
   As a more valid and informative alternative, this study prioritizes descriptive-comparative analysis which focuses on:
   a. absolute and percentage change magnitudes,
   b. consistency of trends between observation periods and
   c. calculation of effect size (Cohen's d) which is independent of sample size.
   The paired sample t-test results presented in Chapter IV serve solely as a discussion material for methodological transparency, namely to demonstrate the limitations of conventional statistical analysis in the context of these data and to strengthen the justification for using a descriptive-comparative approach.

RESULTS AND DISCUSSION

This study analyzes the impact of the Weigh-In-Motion (WIM) system installation on traffic characteristics on the Pekanbaru-Dumai toll road. Data used covers three months before and three months after WIM installation for three main variables: total vehicle volume, average speed of freight vehicles, and the number of accidents involving freight vehicles.

Table 1. Descriptive Statistics of Research Variables (N = 3 Months)

Variables	Period	Minimum	Maximum	Average	Standard Deviation
Total Vehicle Volume	Before	69,764	76,838	72,357.67	3,896,152
Total Vehicle Volume	After	49,579	80,641	67,233.33	15,960,501
Freight Vehicle Speed (km/h)	Before	26.6	32.5	29.88	3.04
Freight Vehicle Speed (km/h)	After	28.6	38.3	32.98	4.9
Number of Goods Vehicle Accidents	Before	2	3	2.67	0.57
Number of Goods Vehicle Accidents	After	1	2	1.33	0.57

1. Total Traffic Volume
   The average volume of freight vehicles before WIM installation was 72,358 vehicles per month with relatively low fluctuation (standard deviation 3,896). After installation, the average volume decreased to 67,233 vehicles, but with significantly higher inter-monthly variation (standard deviation 15,961). This indicates a more dynamic change in traffic patterns post-intervention.
2. Average Speed of Freight Vehicles
   The average speed of freight vehicles before the intervention was 29.88 km/h. After the WIM installation, the average speed increased to 32.99 km/h, with a wider data distribution, indicating greater speed diversification between vehicles and over time.

3. Freight Vehicle Accident Rate
   The average number of accidents before WIM installation was 2.67 per month. After the intervention, this number decreased to 1.33 per month, with the same level of variation (standard deviation 0.58), indicating a steady and consistent decline.

To see the magnitude and direction of change more clearly, a comparative analysis was carried out by calculating the average difference and percentage change, as presented in Table IV.2.

Table 2. Summary of Changes and Consistency of Trends after WIM Installation

Variables	Average Before	Average After	Difference (Δ)	Percentage Change	Monthly Trend Consistency
Total Volume	72,357.67	67,233.33	-5,124.34	-7.08%	2 months up, 1 month down (average down)
Speed	29.88	32.99	+3.11	+10.41%	2 months up, 1 month down (average up)
Accident	2.67	1.33	-1.34	-50.00%	2 months down, 1 month stable (average down)

Descriptively, Table IV.2 shows that WIM installation is followed by:
1. Total traffic volume decreased by 7.08%.
2. The average speed of goods vehicles increased by 10.41%.
3. A very significant reduction in the number of goods vehicle accidents, namely 50%.

Analysis of the consistency of the monthly trends (see Appendix for detailed data) shows that despite monthly fluctuations, the direction of the average changes for the three variables already shows a clear pattern in this three-month observation period.

Visualizations of the comparison of the before and after averages for the three variables are presented in Figures 3,4 and 5, which clarify the differences that occur.

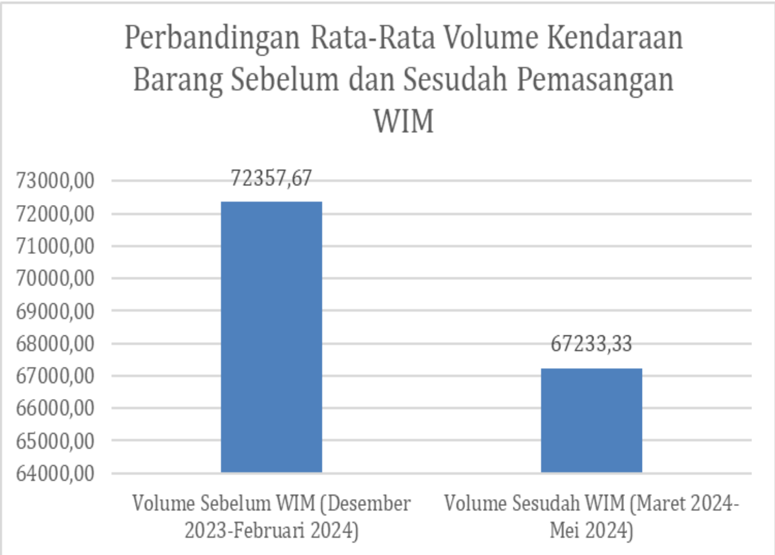

Figure 3 Comparison of Average Freight Vehicle Speed Before and After WIM Installation

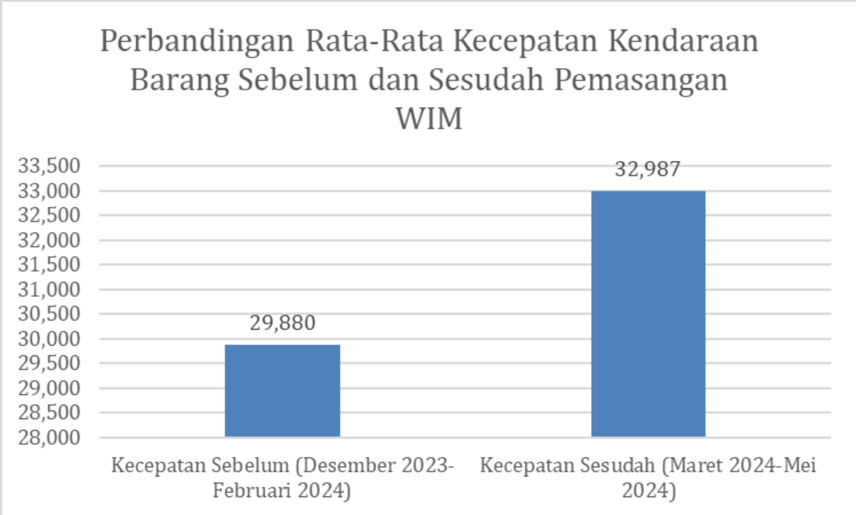

Figure 4. Comparison of Average Freight Vehicle Speed Before and After WIM Installation

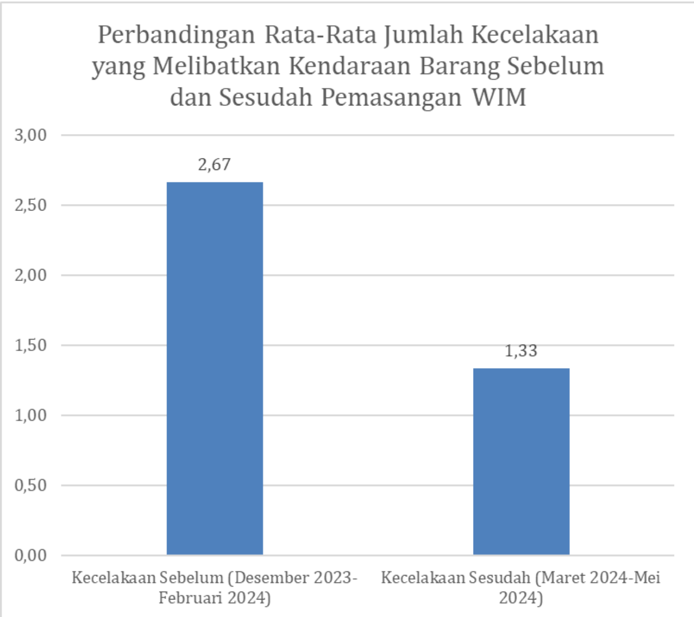

Figure 5 Comparison of the Average Number of Goods Vehicle Accidents Before and After WIM Installation

The graphs above visually confirm the findings from Table IV.2, the "after" column for volume and accidents is shorter than the "before", while for speed, the "after" column is taller.

Research result

This section discusses the results of further statistical testing and provides an in-depth interpretation of the change patterns described in sub-chapter 4.1. The discussion is linked to the theoretical framework and causal logic to answer the research problem formulation.

Supporting Statistical Test Results and Significance

As explained in the methodology, to maintain analytical transparency, an inferential statistical test using the Paired Sample T-Test was conducted. The results of this test, presented in Table 4.3, serve as a basis for discussion regarding the limitations of applying conventional significance tests to data with a limited number of observations (N=3). Although the Paired Samples T-Test did not show statistical significance ($p > 0.05$) due to the limited sample size (N=3), the change trends for the three research variables were in line with the proposed hypothesis.

It should be emphasized that the paired t-test results in Table 4.3, which show p values > 0.05 for all three variables, do not indicate no effect, but rather are a direct consequence of the limited statistical power resulting from the small sample size (N=3). In the context of a policy evaluation with limited data such as this, practical significance, as measured by the magnitude of change and effect size, has greater validity than statistical significance. Therefore, the following discussion will focus on the interpretation of Cohen's d and percentage change as more relevant measures of impact.

Table 3 Paired Sample T-Test Results (As a Demonstration of Statistical Limitations) and Effect Size Cohen's d

Variables	t	df	Sig. (2-tailed)	Statistical Decision	Cohen's d	Interpretation of Effect Size
Volume	0.677	2	0.568	Not Significant ($p > 0.05$)	0.391	Small-Medium Effects
Speed	-0.677	2	0.568	Not Significant ($p > 0.05$)	-0.391	Small-Medium Effects
Accident	2,000	2	0.184	Not Significant ($p > 0.05$)	1,155	Big Effect

Interpreting effect size using Cohen's d provides a more nuanced perspective than simply statistical significance. Based on interpretation guidelines (Cohen, 1988), where $d \approx 0.2$ is considered a small effect, $d \approx 0.5$ a medium effect, and $d \geq 0.8$ a large effect, the analysis can be as follows:

1. Accident Rate ($d = 1.155$)
   This value far exceeds the 0.8 threshold, and is therefore classified as a LARGE effect. This provides strong evidence that a 50% reduction in accidents represents a substantial impact of WIM installation.
2. Traffic Volume ($d = 0.391$) and Average Speed ($d = 0.391$)
   Both values fall within the SMALL to MEDIUM effect range. This classification aligns with the observed percentage changes (7.08% and 10.41%), which, while not as drastic as accidents, still indicate a discernible influence. The consistent direction of change (volume decrease, speed increase) (and supported by theoretical logic) strengthens the conclusion that WIM does indeed influence these two variables, although the strength of the association is more moderate.

Thus, the effect size analysis not only strengthens the findings for the accident variables, but also provides the proper context for understanding the magnitude of the influence of WIM on volume and speed.

Evaluation of the Research Hypothesis

Based on the synthesis of the evidence that has been described, starting from consistent descriptive changes, measurable effect sizes, to coherent causal logic, the evaluation of the research hypothesis proposed in Chapter II can be formulated as follows.

1. Evaluation of the Null Hypothesis (H_0)
   H_0 states that there is no significant difference in the average traffic volume, speed, and accident rate of goods vehicles before and after the installation of Weigh-In-Motion. The empirical findings of this study do not support this statement. The data show a significant difference and point to a systematic pattern, namely a decrease in total volume, an increase in average speed, and a drastic decrease in the accident rate. Therefore, H_0 is rejected.
2. Evaluation of the Alternative Hypothesis (H_1)
   H_1 states that there is a significant difference in the three variables. The results of the analysis provide strong support for H_1. The observed pattern of changes is not a random fluctuation, but rather forms a logical impact narrative of the WIM intervention, namely the filtering mechanism that reduces problematic vehicles (ODOL), which in turn

increases the homogeneity and safety of traffic flow. Thus, H_1 is accepted. It can be concluded that the installation of the Weigh In Motion system has a significant (and practically meaningful) impact on reducing traffic volume, increasing average speed, and reducing the accident rate of goods vehicles on the Pekanbaru-Dumai Toll Road.

The rejection of H_0 and acceptance of H_1 is based on practical significance as indicated by the magnitude of the change and effect size, considering the limitations of conventional statistical significance tests on data with limited N as explained previously.

Discussion

After descriptively presenting the statistical findings in the previous sub-chapter, this section continues the analysis with an in-depth discussion of the hypothesis testing results and the identified patterns of change. The discussion goes beyond simply repeating numbers or tables, but rather seeks to interpret the meaning behind the findings by referring to the established theoretical framework. Each pattern of relationships between variables will be elaborated using causal logic and examined for consistency with relevant theories, previous research, and the empirical context in the field. Thus, this sub-chapter serves as an intellectual bridge to substantively answer the research problem formulation and provide scientific justification for the significance of the findings.

1. Discussion of the Effect of WIM on Total Traffic Volume

   The finding of a 7.08% decrease in total traffic volume following the installation of the WIM is a key indicator confirming the filtering mechanism's effectiveness. The WIM acts as an effective deterrent for goods vehicles operating under ODOL conditions. The presence of this automated monitoring system increases the perceived risk of sanctions, thus encouraging operator behavioral adaptations, including:

   a. Shifting ODOL vehicle routes to non-toll roads to avoid inspections.
   b. Delay or consolidation of shipments until the cargo complies with regulations.

This decrease in volume, despite measuring total volume (all vehicles), indicates that the impact of screening problematic vehicles was significant enough to reduce the aggregate number. The increasing monthly fluctuations (standard deviation increased from 3,896 to 15,961) reflect the transition phase and uncertainty of new travel patterns.

From a traffic management perspective, the decrease in total volume of 5,124 vehicles per month (-7.08%) does not necessarily indicate a decrease in road utility, but rather efficiency in vehicle composition. This decrease is predominantly due to the filtering of problematic goods vehicles (ODOL). Practically, this average reduction of ± 171 vehicles/day has the potential to significantly reduce the equivalent axle load (ESAL) on the pavement structure. Assuming that one ODOL vehicle is equivalent to tens to hundreds of light vehicles in damaging the road, this volume reduction can shorten routine maintenance intervals and reduce the rate of deterioration of the Pavement Condition Index (PCI) value, thereby providing savings in infrastructure life-cycle costs for toll road operators.

The total volume reduction of 5,124 vehicles per month does not merely indicate a decrease in road utility, but rather indicates selective efficiency within the system. From an infrastructure asset management perspective, the reduction in problematic vehicles (ODOL) has significant technical implications. Excessive axle loads from ODOL vehicles are a major factor in accelerating pavement deterioration. Conservatively assuming that one ODOL vehicle is equivalent to 10-30 times the damaging power of a light vehicle, this volume reduction translates into a significant reduction in the equivalent single axle load (ESAL). This has the potential to extend the service life of toll road pavements and delay the need for major maintenance, thereby providing significant life-cycle cost savings for toll road operators (BUJT).

2. Discussion of the Effect of WIM on the Average Speed of Freight Vehicles

   The 10.41% increase in average speed is a logical consequence of the improved traffic composition. The main mechanism is the homogenization effect:

   a. Slow Vehicle Reduction

      The filtering of ODOL trucks, which naturally move slowly due to overloading, removes a natural bottleneck in traffic flow.

   b. Density Reduction

      The reduction in total volume directly reduces vehicle density on toll roads, creating more space for movement.

   The combination of these two factors results in a smoother, more homogeneous flow, with reduced speed variance between vehicles. This increase in speed does not indicate a violation, but rather greater operational efficiency among the remaining vehicles (the majority of which are compliant).

   The 3.11 km/h (+10.41%) increase in average speed has significant operational and economic implications. This improvement indicates an improved Level of Service (LoS) on the toll road, by reducing travel time. Practically, on a 131 km section, the average travel time savings can reach approximately 6-7 minutes per trip for freight vehicles. For logistics operators, this accumulated time savings can increase vehicle productivity by potentially adding one trip per week on medium-distance routes or reducing variable operational costs such as fuel consumption and vehicle maintenance. Furthermore, this higher speed homogenization directly reduces speed variance, a key predictor in accident frequency models.

Furthermore, this increase in speed is a proxy for improved traffic stream homogeneity and reduced dynamic interference from slow vehicles, which directly contributes to an increase in the Level of Service (LoS) of the toll road as a whole.

1. *Discussion of the Influence of WIM on the Accident Rate of Goods Vehicles*

   The sharp reduction in accidents (-50%) with a large effect size (d=1.155) represents the most significant integrative impact. This finding aligns with traffic safety theory, which states that flow homogeneity is a key predictor of accident reduction. The causal logic can be summarized as follows:

   a. Exposure Factor Reduction

      Reducing vehicle volume, especially high-risk vehicles (ODOL), directly minimizes the potential for conflict interactions on the road.

   b. Vehicle Performance Improvement

      A properly loaded goods vehicle has much better stability, braking and maneuverability, reducing the possibility of loss-of-control.

   c. Increased Flow Homogeneity

      As discussed previously, the combination of lower volumes and more uniform speeds drastically reduces speed variance. In the safety literature, low speed variance is strongly correlated with reduced crash frequency and severity.

This absolute reduction of 1.34 incidents per month (-50%), if extrapolated, is equivalent to preventing approximately 16 accidents per year on this toll road. Referring to accident cost studies often used in safety benefit analysis, every serious accident involving a freight vehicle can cause enormous socio-economic costs, including property damage costs, medical costs, lost productivity, and subsequent congestion costs due to the incident. Thus, WIM interventions not only save lives and prevent suffering, but also provide substantial economic benefits in the form of reducing the external costs of accidents that must be borne by the transportation system and the wider community.

Thus, WIM not only prevents accidents through law enforcement, but more fundamentally, creates a systemic environment that is inherently safer for all road users.

The absolute decrease of 1.34 incidents per month (or ~16 incidents per year) has the most critical implications from both a humanitarian and economic perspective. Referring to the accident cost calculation methodology commonly used in transportation policy analysis, each serious accident involving a freight vehicle can cause socio-economic losses in the order of hundreds of millions to billions of rupiah, which includes components such as property damage costs, medical and rehabilitation costs, loss of economic output due to victims (human capital/output loss), and secondary congestion and logistics disruption costs. Thus, the WIM intervention not only acts as a law enforcement tool but also functions as a safety investment instrument that provides returns in the form of preventing enormous economic and social losses. The impact of this 50% reduction represents a dramatic improvement in safety performance on the toll corridor.

2. Synthesis and Implications of Findings

Holistically, these three findings form a coherent and mutually reinforcing causal narrative:

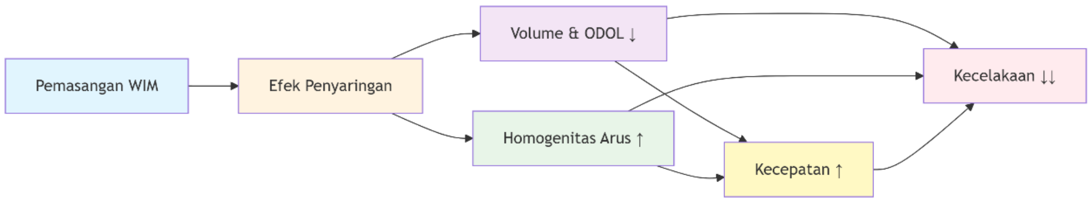

Figure IV.4 Implications of Findings

The implications of these findings are:

a. For Toll Road Managers
WIM should be viewed as a strategic investment in safety and operational management, not simply a filtering tool. Its positive impact is twofold: improving compliance while reducing the socio-economic costs of accidents.

b. For Policy Makers
Public communication regarding WIM needs to emphasize the safety and smoothness benefits for all compliant road users, in order to build positive perceptions and public support.

c. For Further Research
Further studies with longer observation periods (longitudinal studies) are needed to further assess the stability of the impacts and the adaptation phase. A quasi-experimental study involving a comparison group (toll roads without WIM) would also be invaluable in more rigorously isolating the effects of WIM.

This study has several limitations that need to be acknowledged:

1. Observation Time Span
The three-month observation period before and after WIM installation was relatively short. Observed changes may reflect short-term effects or initial shock from transit operators. Long-term traffic behavior and patterns (long-term adaptation) may not have been fully captured.

2. Design Without Control Group
This study used a one-group pretest-posttest design. The absence of a similar comparison toll road section (control group) without WIM limits the ability to completely isolate the influence of WIM from external factors (such as seasonal economic fluctuations and other national policies).

3. Secondary Data Sources

The data was obtained from toll road management records. While reliable, the study lacked direct control over the collection methods and the potential for human error in the initial recording.

4. Limitations of Statistical Analysis

   The use of three pairs of monthly data (N=3) limits the application of conventional inferential statistical tests. While descriptive-comparative analysis and effect size analysis provide valid insights, rigorous statistical generalization is not possible. The findings are more indicative than statistically conclusive.

   Nevertheless, the large effect sizes and logical consistency of the changes in all three variables (volume decrease, speed increase, and crashes decrease) provide a strong initial indication of a positive impact of WIM. This limitation, however, opens up opportunities for more robust follow-up research.

CONCLUSION

Against Total Traffic Volume

Based on the analysis, it was found that after the installation of WIM, there was a 7.08% decrease in total vehicle volume. This finding indicates a potential filtering effect on ODOL vehicles, which aligns with the purpose of WIM installation. However, because this study did not control for external factors such as homecoming restrictions and seasonal fluctuations, the decrease in volume cannot be entirely attributed to WIM alone. Therefore, a more appropriate conclusion is that WIM is correlated with the decrease in volume, with the caveat that other factors may have contributed.

On the Average Speed of Goods Vehicles

Based on the analysis, the average speed of goods vehicles increased by 10.41% after the installation of WIM. This increase indicates that the homogeneity of traffic flow may improve due to the reduction of slow-moving ODOL vehicles. However, the post-WIM average speed (32.99 km/h) is still below the minimum expected on toll roads, so this increase cannot be claimed as a substantial improvement in logistics performance. This finding is more appropriately interpreted as a promising initial indication, with the caveat that external factors such as a reduction in overall vehicle volume may also contribute to the observed speed increase.

On the Accident Rate of Goods Vehicles

The most significant finding in this study was a 50.00% decrease in the number of accidents involving freight vehicles after the installation of WIM, with a relatively large effect size (Cohen's d = 1.155). This decrease is thought to be related to the reduced volume of high-risk vehicles and improved homogeneity of traffic flow, which theoretically can reduce speed variance, a factor known to contribute to accident risk. However, because this study did not control for external factors such as the policy of restricting freight vehicles during the homecoming period and seasonal fluctuations, the decrease in accidents cannot be entirely attributed to WIM alone. However, the large decrease (50%) and large effect size strongly indicate that WIM contributes substantially to improving traffic safety on the Pekanbaru-Dumai toll road.

Holistically, this study shows that the installation of WIM has created systemic changes in traffic characteristics. WIM functions not only as an enforcement tool, but also as a traffic management tool that successfully creates a profitable trade-off: a limited reduction in volume is exchanged for an increase in efficiency (speed) and, most importantly, a significant increase in safety. The pattern of "Volume Down, Speed Up, Accidents Drastically Down" found forms a coherent causal narrative about the effectiveness of WIM in creating a more orderly, smooth, and safe traffic environment.

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