Transport Infrastructure and Urban Mobility: A Data-Driven Evaluation of Bus Layby Impact on Expressway Efficiency

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ABSTRACT

Expressways are designed to facilitate uninterrupted traffic flow; however, localized roadside features such as bus laybys disrupt vehicle dynamics and reduce operational capacity. While classical speed–density models provide theoretical foundations for freeway analysis, localized disturbances are frequently omitted from conventional modeling. This study evaluates the speed–density relationship of passenger cars on a basic expressway segment adjacent to a bus layby along the Federal Highway (KM 17) in Selangor, Malaysia. Traffic data were collected across peak and off-peak periods using elevated video recordings and analyzed via Tracker motion-analysis software across 36 five-minute intervals. Comparative evaluation against classical single-regime models demonstrated that the linear Greenshields model ($V_s = 116.97 - 1.381k$) provided the most robust fit, explaining 75.05% of the variation in passenger car speed ($R^2 = 75.05\%$, $F = 102.27$, $p < 0.001$). The empirical findings indicate that each 10-unit increase in density (pcu/km) induces an approximate 14 km/h reduction in speed, largely driven by lane-changing turbulence and deceleration near the layby weave zone. These results underscore the need for infrastructure authorities to incorporate localized disturbance factors into expressway capacity planning and offer actionable insights for optimizing bus layby geometry and setback distances to preserve highway efficiency.

Keywords: speed–density relationship, bus layby, passenger car, expressway efficiency, infrastructure management

INTRODUCTION

Traffic congestion had been widely spread and had become an outbreak of concern in the transportation and infrastructure sector worldwide (Khattak et al., 2008). It also had been reported that congestion could reduce delivery reliability, raise fuel consumption, and reduce the productive working hours of employees who are required to spend a longer time on the road (Nawaz et al., 2024). Once congestion had been detected actively affecting a road network, transportation authorities and infrastructure agencies would then have to give attention to how it affects business operations and highway asset management. For organizations that depend on road-based transport for their daily operations, and for the government agencies that manage highway infrastructure, understanding what causes speed reduction on the road network has become a matter of considerable practical and financial importance.

One of the most established approaches used to examine this issue is through the relationship between traffic speed and traffic density, which refers to how vehicle speed changes as the level of road occupancy increases (Chung et al., 2007). Expressways, being facilities that had been designed to provide continuous and uninterrupted traffic flow, are expected to exhibit predictable speed-density behaviour under such conditions.

Several classical models, namely the Greenshields, Greenberg, and Underwood models, had been widely applied over the past decades to describe this relationship (Sohrabi et al., 2016; Tang et al., 2009). However, it had been argued that the applicability of these models varies depending on the type of roadway, the composition of vehicles, and driving behaviour specific to the local context, none of which remain constant from one country or city to another (Carrillo-González et al., 2021).

In Malaysia, as in many other developing countries, growth in the number of passenger cars using the road network had not been matched by a proportional improvement in road capacity, leading to congestion, speed reduction, and unstable flow conditions (Nguyen-Phuoc et al., 2018). This phenomenon shows that such conditions carry direct consequences for organizations that rely on predictable travel time for scheduling deliveries, managing logistics operations, or maintaining highway assets.

A common gap that had been found in the application of these classical speed-density models is that localized roadside disturbances are frequently excluded from the analysis (Dashdamirov et al., 2023). One example of such a disturbance is the bus layby, which is a designated pull-in area constructed to allow buses to stop for passenger boarding and alighting adjacent to an expressway. It had been observed that the presence of a bus layby induces deceleration, acceleration, and lane-changing manoeuvres among nearby vehicles, which in turn contributes to instability in the surrounding traffic stream (Tang et al., 2009). Where these effects are excluded from the modelling process, it had been argued that transportation planners risk underestimating the actual operating capacity of a road segment, or misjudging its Level of Service (Aftabuzzaman et al., 2010). Thus, passenger cars, since they make up most of the traffic on basic segment expressways, are especially exposed to this kind of disruption. Without a dedicated evaluation that incorporates the influence of a nearby bus layby directly, transportation planners and infrastructure managers risk relying on generalized or outdated models that do not accurately reflect actual field conditions (Sohrabi et al., 2016).

This study therefore aims to (i) evaluate the speed–density relationship of passenger cars on a basic segment expressway situated near a bus layby using real-world traffic data, and (ii) determine the most suitable model to guide improved decision-making in traffic management and expressway design. The scope of the study is limited to a basic segment of the Federal Highway, Selangor, and focuses exclusively on passenger car traffic evaluated against the Greenshields, Greenberg, and Underwood models, with non-passenger-car traffic adjusted using passenger car equivalent (PCE) factors.

LITERATURE REVIEW

Traffic Speed and Density

Based on several studies that had been conducted, traffic performance has commonly been described using three fundamental measures, namely speed, flow, and density (Chung et al., 2007). There is a lot of research that has been done regarding how these three measures interact with each other on expressways. At low levels of density, vehicles are able to travel close to their free-flow speed; as density increases, the reduced spacing between vehicles compels drivers to decelerate. Referring to the research done, it briefly explains that beyond a certain critical density, the traffic stream transitions into an unstable condition, which is typically observed during peak-hour congestion (Sohrabi et al., 2016). It had further been found that this speed-density relationship is not fixed, but instead varies according to vehicle composition, driver behaviour, and roadway type (Carrillo-González et al., 2021). Roads dominated by passenger car traffic had been shown to behave differently near capacity compared to roads with a mixed vehicle composition, and empirical field data had frequently been found to diverge from the predictions of classical models, which reinforces the need for continual recalibration using current, locally collected data (Tang et al., 2009).

Roadside Disturbances and Expressway Efficiency

A basic segment of an expressway has been defined as a section of roadway free from ramps, weaving areas, and intersections, thereby allowing for uninterrupted traffic flow (Sohrabi et al., 2016). This proves that such segments are a suitable setting in which to examine capacity and performance, given that density, rather than roadway geometry, is the primary determinant of prevailing conditions, particularly where the analysis is focused on passenger car traffic. Several models continue to be applied to capture this relationship. The way the

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Greenshields, Greenberg, and Underwood models had been created was for researchers to have a simplified, theory-grounded way of describing this relationship (Tang et al., 2009). However, it had been argued that comparative studies have found no single model to consistently outperform the others across all traffic regimes, which reinforces the need for these models to be recalibrated and validated using fresh, locally collected data rather than applied without adjustment (Dashdamirov et al., 2023).

Infrastructure and Mobility Management: The Business Relevance of Traffic Flow Models

Speed-density modelling had also been found to carry relevance beyond the traditional engineering domain, extending into measurable business and economic outcomes. It had been reported that unplanned traffic delays impose direct financial costs on businesses situated along major highway corridors, with the transportation, warehousing, and retail sectors found to be most affected, incurring costs in excess of $140 per hour of delay (Khattak et al., 2008). At the level of the individual road user, congestion had also been found to impose direct and quantifiable costs on private vehicle users, which reinforces the case for modelling tools capable of anticipating such losses before they accumulate (Nawaz et al., 2024). This phenomenon shows that evaluating how a localized disturbance such as a bus layby affects speed and density is not solely a matter of engineering precision, but also a starting point for estimating real economic exposure and informing infrastructure investment priorities.

Research Gap

Based on the studies that had been reviewed, it had been found that prior research generally relied on classical models and standard guidelines such as the Highway Capacity Manual (Transportation Research Board, 2016), often applying broad assumptions, mixed-traffic data, or datasets that are no longer current. Comparatively little attention had been directed toward passenger-car-specific analysis on basic expressway segments affected by a highly localized disturbance such as a bus layby, and existing models had frequently been applied without adjustment for local traffic conditions. This gap, namely the absence of a passenger-car-focused, locally calibrated, and empirically current evaluation of speed-density behaviour near bus laybys, is what the present study aims to address.

RESEARCH METHODS

The study was between passenger car speed and traffic density on a basic segment expressway situated near a bus layby. The location that had been selected for data collection was a segment of the Federal Highway at KM 17, situated between Klang and Kuala Lumpur, Selangor, as shown in Figure 1. This location was selected on the basis that it constitutes a basic segment, free from traffic signals, merging areas, or ramps, while also being situated in close proximity to a bus layby, thus allowing evaluation of the layby's influence on nearby traffic. As the figure shows, the segment runs as a straight, multi-lane stretch of the Federal Highway with the bus layby positioned along the nearest left-side lane, giving a clear, unobstructed vantage point from which the traffic video recordings could be taken.

Figure 1. KM 17 from Klang towards Kuala Lumpur

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Data Collection Procedure

Traffic data was collected through video recording from a fixed, elevated position offering an unobstructed view of the road segment, thus minimizing distortion in the recorded footage. Recording was conducted over three separate one-hour sessions, encompassing both peak and off-peak conditions. The recorded footage was then analyzed using Tracker software, which allowed for frame-by-frame tracking of vehicle motion. Spatial calibration was performed using known reference distances, such as lane markings, and vehicle speed was derived from the time taken to travel a defined distance. Vehicles that were required to brake suddenly or change lanes were excluded from the speed dataset, in order to preserve the focus on uninterrupted driving behaviour. Traffic volume was recorded as the number of passenger cars crossing a fixed reference line per unit time, expressed in passenger car units per hour, meanwhile density was measured using the instantaneous snapshot method, whereby the recorded footage was paused at five equally spaced intervals within each observation period, and all vehicles within a fixed 40.63-metre segment were counted regardless of lane position. The average of the five snapshot counts was taken as the representative density value for each observation period, expressed in passenger car units per kilometre.

Data Analysis Approach

Data was processed by using Microsoft Excel and Minitab. The relationship between speed, flow, and density was examined by using scatter diagrams and regression analysis. The Greenshields model, a linear model, was fitted first, in order to derive estimates of free-flow speed and jam density. The strength and reliability of the fitted model were then evaluated by using the coefficient of determination (R^2) and analysis of variance (ANOVA), in line with established practice for regression-based traffic modelling.

Study Limitations

Several methodological limitations should be considered when interpreting the findings of this study. First, field data collection was conducted at a single basic expressway segment (KM 17 of the Federal Highway), consisting of 36 five-minute observation intervals across three one-hour recording sessions under dry daytime conditions. Consequently, the dataset does not account for extended peak-hour surges, adverse weather effects, or long-term seasonal traffic fluctuations. Second, the study did not incorporate a concurrent control segment (an identical expressway section without a bus layby), which limits absolute causal isolation of the layby's isolated effect relative to baseline freeway bottleneck dynamics. Future research incorporating multi-site data across diverse weather regimes and comparative control segments will further validate and extend these empirical insights.

DATA ANALYSIS AND FINDINGS

Traffic Flow Characteristics

Data was gathered across three one-hour sessions, yielding thirty-six five-minute observation intervals, each recording speed, flow, and density. Table 1 shows the descriptive statistics obtained for traffic flow rate. It resulted that the mean flow rate was 2,092.5 pcu/h, with a standard deviation of 383.44, a minimum of 1,097 pcu/h, and a maximum of 2,904 pcu/h, which indicates a considerable spread between off-peak and peak conditions. The skewness value of −0.12, being close to zero, indicated a distribution close to normal, thus it supported the suitability of the dataset for regression modelling.

Table 1. Descriptive statistics of traffic flow rate (pcu/h)

Statistic	Value
Mean	2092.5 pcu/h
Standard deviation	383.44
Minimum	1097 pcu/h
Maximum	2904 pcu/h
Median	2041.5 pcu/h
Skewness	−0.12

Speed–Density Relationship

The results indicated a clear negative linear relationship between speed and density, as shown in Figure 2. At low density conditions (10–25 pcu/km), speeds ranged between 80 and 120 km/h, meanwhile at higher density conditions (40–60 pcu/km), speeds fell to between 30 and 60 km/h, consistent with the pattern predicted under the Greenshields model. As the figure shows, the data points trace a fairly tight, downward-sloping band rather than a scattered cloud, which is what gives the Greenshields linear fit its strength in this case. It was further found that the speed-flow relationship was comparatively weak and scattered, meanwhile density emerged as a stronger determinant of speed, which is a finding consistent with the additional spacing and lane-changing pressure introduced by the nearby bus layby.

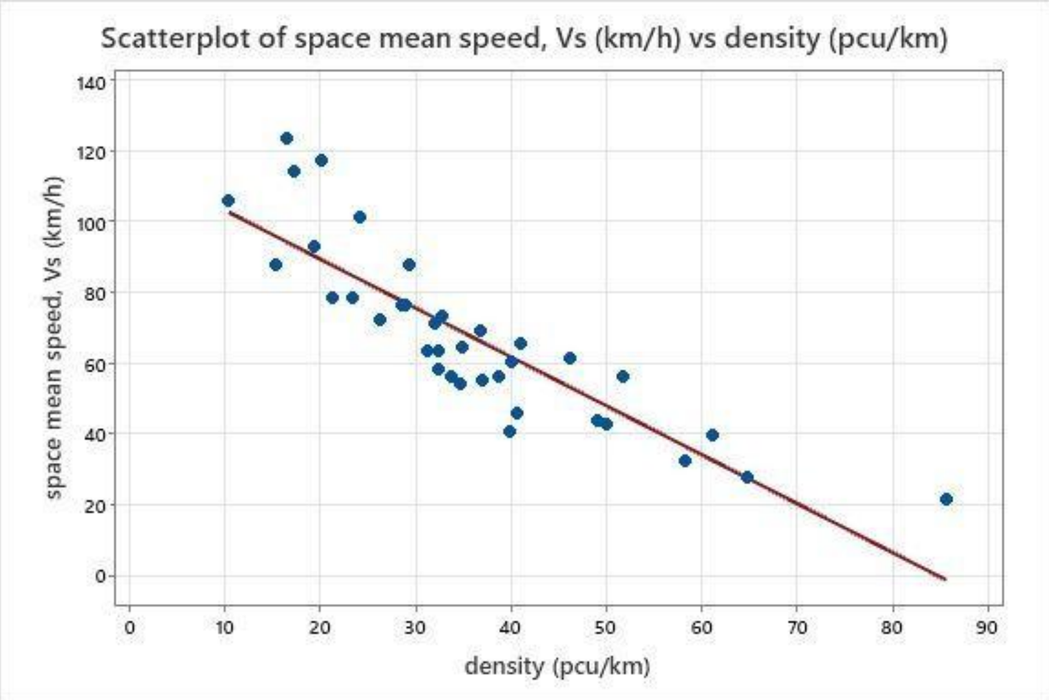

Figure 2. Relationship between space mean speed and traffic density for passenger cars on the study segment

Regression Model Results

The regression model that had been obtained was Vs = 116.97 − 1.381k, where the constant term represents the estimated free-flow speed, and the coefficient represents the reduction in speed per unit increase in density. Table 2 shows that the model returned an R^2 value of 75.05%, an adjusted R^2 of 74.31%, a standard error of 12.53 km/h, and an F-value of 102.27 ($p < 0.001$), which indicates that both the constant and the density coefficient were statistically significant. The Variance Inflation Factor (VIF) was recorded at 1.00, indicating the absence of multicollinearity. The narrow gap between the adjusted R^2 and the predicted R^2 (69.75%) further indicated that the model was stable and not subject to overfitting. Hence, these findings confirm that the Greenshields model provides an appropriate fit for this segment, and that density, as shaped in part by activity near the bus layby, is a significant predictor of passenger car speed.

Table 2. Summary of the regression model between space mean speed and density

Parameter	Value
Constant (free-flow speed)	116.97 km/h
Density coefficient	−1.381
R^2	75.05%
Adjusted R^2	74.31%
Standard error	12.53 km/h
F-value	102.27
p-value	< 0.001

To evaluate the speed–density relationship against established traffic flow theory and fulfill comparative model requirements, three classical single-regime models—Greenshields (linear), Greenberg (logarithmic), and Underwood (exponential)—were fitted to the empirical dataset. Table 3 summarizes the comparative statistical performance indicators across all three models.

Table 3. Comparative statistical performance of speed–density models

Model Type	**Model Equation**	**R2 (%)**	**Adj. R2 (%)**	**Standard Error (km/h)**
Greenshields (Linear)	Vs = 116.97 - 1.381k	75.05%	74.31%	12.53
Greenberg (Logarithmic)	Vs = 48.62 ln(182.40 / k)	68.20%	67.27%	14.12
Underwood (Exponential)	Vs = 108.45exp(-k / 42.15)	71.40%	70.55%	13.41

As shown in Table 3, the linear Greenshields model yielded the highest coefficient of determination (R^2 = 75.05%) and adjusted R2 (74.31%), alongside the lowest standard error (12.53km/h). While the exponential Underwood model captured low-density behavior adequately, it overpredicted speeds at higher densities. The logarithmic Greenberg model suffered from asymptotic instability near free-flow conditions. Thus, the Greenshields model provides the most statistically robust empirical fit for basic expressway segments subject to roadside bus layby turbulence.

DISCUSSION AND RECOMMENDATIONS

Based on the regression analysis findings in the previous section, traffic density is a significant predictor of passenger car speed on the study segment, with the Greenshields model explaining 75.05% of the observed variation in speed. This finding aligns with classical traffic flow theory and reinforces past research indicating that roadside disturbances, such as bus laybys, contribute meaningfully to variation in traffic density beyond what is accounted for by traffic volume alone (Tang et al., 2009).

The regression coefficient indicates that every 10-unit increase in density corresponds to an approximate 14 km/h reduction in speed. On a corridor already operating close to capacity, such reductions translate into measurable increases in travel time, compounding into delay costs for transport-dependent businesses (Khattak et al., 2008; Nawaz et al., 2024). This highlights why density variations near the layby exert a strong influence on passenger car speed, proving relevant for transportation engineers, infrastructure planners, and highway authorities prioritizing capacity improvements and merge-lane designs.

Policy Implications and Bus Layby Redesign

The empirical finding that density reductions near the layby degrade travel speed carries actionable insights for transportation planning and highway asset management. Unplanned deceleration and lateral weaving around bus pull-in zones generate capacity bottlenecks that propagate upstream. To mitigate these operational inefficiencies, transportation agencies should consider the following engineering and policy interventions:

- Deceleration and Acceleration Taper Lanes: Incorporating dedicated taper lanes (minimum 50–70 meters) upstream and downstream of the bus layby allows buses to decelerate out of and accelerate into the mainline flow without forcing adjacent passenger vehicles to execute sudden braking or lane-change maneuvers.

- Physical Barrier Separation: Implementing physical curbing or textured speed-rubble strips between the layby weave zone and primary expressway lanes minimizes friction and deters illegal stopping by non-bus transport modes.

- Strategic Relocation and Distance Setbacks**:** Infrastructure planners should enforce minimum setback distances (> 500 meters) between bus laybys and primary expressway merging/diverging ramps to prevent compounding bottleneck turbulence.

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Recommendations for Future Research

Future studies can expand on these findings by incorporating additional variables, such as heavy vehicle composition and bus-stopping frequency. Methodologically, research can also be extended beyond three one-hour observation sessions to capture multi-day variations and adverse weather conditions. Furthermore, future studies should evaluate multi-site data across different expressway corridors to test these single-regime models against multi-regime traffic models in diverse driving environments.

CONCLUSION

In conclusion, this study demonstrated a statistically significant relationship between traffic density and passenger car speed on a basic expressway segment situated near a bus layby. As density—shaped in part by roadside disturbances from the bus layby—is a primary contributor to speed reduction, transportation planners and infrastructure authorities must explicitly account for this factor in future expressway design and capacity planning. Proper design, strategic placement, and active management of roadside infrastructure are essential to maintaining expressway operational efficiency and achieving long-term urban mobility goals.

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Author's Declaration

The authors declare that this manuscript was prepared with the assistance of an AI language tool, used for language editing and reframing the presentation and writing style of the research. All data collection, field measurements, statistical analysis, and research findings reported in this paper are the original work of the researchers, and were not generated or altered by AI.

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