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Integrated Assessment of Passing Maneuvers Based on Road and Vehicle Characteristics

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Abstract

This paper investigates the interaction between vehicle dynamics parameters and road geometry during the passing process. The methodology is based on a realistic representation of the passing task with respect to roadway's posted speed and the ability of the passing (examined) vehicle to perform such maneuvers, utilizing an existing and rigorously validated vehicle dynamics model. However, the specific analytical model is computationally demanding. Therefore, regression models were derived to determine passing sight distances (PSDs) by arranging combinations of 4 critical vehicle – roadway parameters; namely, roadway's posted speed, passed vehicle speed, horsepower rates and slope values. The analysis revealed that speed related variables impact excessively PSD, while the effect of roadway slope becomes increasingly significant at higher values. The lognormal modelling approach for predicting PSDs was found efficient and may be useful to researchers and practitioners aiming to evaluate the interaction of the utilized road – vehicle parameters in terms of determining PSDs as well as passing zones. Although more advanced communication between vehicles or between vehicles and road environment seems a prerequisite in order integrated guidance during passing maneuvers to be enabled, the present research consists an opening paradigm of how the passing process can be standardized and therefore deployed in advanced driver assistance systems (ADAS).

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1. Introduction and problem statement

Two-lane rural roads constitute a vital component of national and regional transportation systems, yet they consistently present one of the highest proportions of severe traffic accidents [European Commission (2024)]. A significant share of these crashes is directly associated with overtaking maneuvers, particularly unsuccessful passing attempts that result in head-on collisions with opposing vehicles or conflicts with the overtaken vehicle traveling in the same direction. As highlighted in numerous studies, including Clarke et al. (1998), Persaud et al. (2004), and Richter et al. (2014), the inherent complexity and risk of the passing process stem from the temporary occupation of the opposing traffic lane, where safety margins are limited and highly dependent on driver judgment, vehicle performance, and roadway conditions.

To mitigate these risks, passing is permitted only within designated roadway segments, commonly referred to as passing zones. The design and placement of these zones rely fundamentally on the provision of adequate Passing Sight Distance (PSD), defined in NCHRP Report 605 (2008), as the minimum distance a driver must be able to see ahead to safely initiate and complete a passing maneuver. PSD is therefore a cornerstone parameter in geometric design, directly influencing both safety and operational performance on two-lane rural roads.

Current design standards, such as those established in the AASHTO Green Book (2018) and the German RAL (2012) guidelines (2012), provide structured methodologies for determining PSD. In the AASHTO framework, PSD is calculated as the sum of four components: the distance traveled during perception–reaction and initial acceleration (d_1), the distance traveled while occupying the opposing lane (d_2), a safety clearance distance (d_3), and the distance covered by an opposing vehicle during the maneuver (d_4). These formulations are based on field studies conducted several decades ago and assume specific driver behaviors, such as a delayed start and a hurried return under opposing traffic conditions. Furthermore, they adopt simplified assumptions regarding vehicle speeds, acceleration rates, and a fixed speed differential between the passing and the impeding vehicle.

Similarly, European practices—such as the German RAL (2012) guidelines—adopt standardized PSD values (e.g., 600 m), derived from predefined vehicle interaction scenarios involving typical passenger cars and heavy vehicles. While these approaches provide practical and conservative design guidance, they inherently rely on idealized and static representations of a highly dynamic process.

A critical limitation of existing design standards is that many of their underlying assumptions no longer adequately reflect contemporary traffic conditions. Vehicle fleets have evolved significantly, now encompassing a wide range of performance characteristics, including high horse-powered passenger cars, heavy goods vehicles with varying load conditions, and emerging vehicle technologies. Moreover, in Mavromatis et al. (2021) it was found that acceleration behavior is highly variable and strongly influenced by roadway grade, vehicle type, and driver input, rather than remaining constant as often assumed in design models.

These limitations become particularly pronounced under non-level terrain conditions. Roadway grades, especially upgrades, can substantially reduce vehicle acceleration and increase the time required to complete a passing maneuver. At the same time, vertical alignment—particularly crest vertical curves—can restrict available sight distance, further constraining passing opportunities. The combined effect of reduced vehicle performance and limited visibility creates critical scenarios that may not be adequately captured by conventional PSD models [Mavromatis et al. (2025)]. Notably, current standards often treat geometric constraints and vehicle performance independently, despite their strong interaction in real-world conditions.

Human factors further increase the complexity of passing maneuvers, as drivers must continuously evaluate opposing traffic, vehicle performance and available sight distance. Previous studies have shown that a substantial proportion of passing-related crashes occur even where nominal PSD requirements are satisfied, highlighting the limitations of purely geometric design criteria (Richter et al., 2017).

The challenges associated with passing are further amplified in traffic environments characterized by limited overtaking opportunities. In such conditions, prolonged delay and driver frustration may promote risk-taking behavior, including passing attempts initiated near the end of designated passing zones or even in prohibited segments. For example, Harwood et al. (2015) reported that up to 92% of passing maneuvers in short passing zones were completed beyond the designated zone limits, compared to only 21% in zones longer than 300 m. Similar findings were reported by Forbes (1990), who observed an increase in forced and abrupt returns as passing zone length decreased.

The presence of heavy vehicles or vehicle platoons exacerbates this situation, as they require significantly longer distances to be overtaken while simultaneously reducing the availability and adequacy of acceptable gaps in the opposing traffic stream. Consequently, both the feasibility and safety margins of passing maneuvers are substantially reduced. Moreover, empirical studies (e.g., Pérez-Zuriaga et al., 2013; Belz, 2019) have shown that drivers frequently exceed posted speed limits during overtaking, likely as a compensatory response to constrained passing conditions. This tendency, combined with the initiation of late or marginal maneuvers, further increases the likelihood of critical conflicts. It is important to note that current design standards predominantly consider single-vehicle passing scenarios and therefore do not adequately reflect the growing prevalence of multi-vehicle interactions, which can significantly increase required PSD and further challenge the safe execution of overtaking maneuvers.

A key parameter that links vehicle dynamics, roadway conditions, and human behavior is the speed differential (ΔV) between the passing and the impeding vehicle. In conventional design practice, ΔV is typically treated as a constant—commonly assumed to be approximately 19 km/h in AASHTO-based models. In reality, however, ΔV is a dynamic variable shaped by driver intent, vehicle performance, and geometric constraints. Drivers may be either unwilling or unable to achieve the assumed speed differential due to safety considerations, limited vehicle capabilities, or adverse roadway conditions such as grades. Consequently, the use of fixed ΔV values may lead to discrepancies between theoretical PSD estimates and actual passing conditions, reinforcing the need for a more realistic and integrated representation of the passing process.

Although climbing lanes and passing lanes can improve safety and operations, their implementation is often constrained by economic and topographical factors (Vetters and Jaehrig, 2015).

Taken together, these considerations highlight a fundamental gap between the simplified assumptions embedded in current design standards and the complex, dynamic nature of real-world passing maneuvers. While existing guidelines provide a necessary framework for design, their deterministic approach may not fully capture the variability introduced by vehicle dynamics, roadway geometry, and human behavior.

Within this context, the objective of the present study is to investigate the interaction between vehicle dynamic parameters and roadway geometry during the passing process for a range of speed differentials (ΔV). By explicitly examining how variations in acceleration capability, roadway grade, and geometric constraints influence passing performance, the study aims to provide a more realistic and integrated representation of PSD requirements. Ultimately, this work seeks to contribute to the refinement of current design practices, supporting the development of more robust, data-driven methodologies that enhance both safety and operational performance on two-lane rural roads while better reflecting real-world driving conditions.

2. Methodology

The proposed Passing Sight Distance (PSD) investigation is grounded on a safe and realistic representation of the passing process on tangent road sections, explicitly accounting for the actual capability of the passing vehicle to successfully complete the maneuver. Emphasis is placed on capturing the dynamic nature of the maneuver, rather than relying on simplified assumptions that may not adequately reflect real-world driving conditions.

The ability of a vehicle to accelerate has been extensively examined in previous research by the authors (Mavromatis et al., 2017; 2018; 2019). In those studies, a comprehensive vehicle dynamics model was developed to evaluate safety as a function of the interaction between road geometry, tire–pavement friction, and key vehicle parameters. Within this framework, vehicle acceleration—among other performance indicators—was directly linked to the available horsepower at the wheels through the introduction of a horsepower utilization factor, denoted as n (%). This factor reflects the practical limitation that vehicles are not continuously operated at their maximum power output, due to driver behavior, engine characteristics, and prevailing traffic conditions.

The following subsection provides a concise overview of the structure and fundamental assumptions of the adopted model, while full mathematical formulations and detailed derivations can be found in the aforementioned references.

2.1. Vehicle Dynamics Approach

It is important to highlight that, both in the original vehicle dynamics model and in the context of the present analysis, acceleration is treated as a variable rather than a constant parameter. This approach allows for a more realistic

simulation of the passing maneuver, as it captures the continuous evolution of tractive effort in response to changing speed, engine performance, and resistive forces.

A comprehensive and physically consistent vehicle dynamics framework was developed to represent the forces governing the vehicle motion under acceleration. All forces and moments are resolved in a moving three-dimensional coordinate system fixed at the vehicle's center of gravity (longitudinal X, lateral Y, vertical Z), enabling the direct incorporation of vehicle characteristics, road geometry, and tire–road interaction, and thus capturing their combined effect on performance.

The model employs a four-wheel representation, accounting for steering inputs, tire sideslip, and lateral load transfer. This allows estimation of the instantaneous wheel loads and the corresponding variation in tire forces, providing a realistic depiction of vehicle stability and force distribution under combined longitudinal and lateral loading.

At the core of the longitudinal dynamics lies the estimation of the available tractive effort at the driven axle (front or rear, depending on the drivetrain configuration). This tractive force is expressed as a function of vehicle speed and the effective power delivered to the wheels, while also incorporating a horsepower utilization factor (n , %), which reflects real-world operating conditions where full engine power is not continuously exploited. The relationship is expressed as:

$$F_x = 745.60 \cdot P/V \cdot n/100 \quad (1)$$

where: F_x : tractive force (Nt); P : net engine horsepower available at driven axle, around 94% of the nominal value [Hardwood et al. (1994)] (hp); V : vehicle speed (m/s); n : horsepower utilization factor (%)

By applying laws of mechanics, the vehicle's instant acceleration, which is expressed as a four-degree polynomial equation, can be formed as a function of vehicle's instant speed as well as driven distance, thus delivering the following differential equation which is resolved by utilizing numerical Runge-Kutta method from Edwards and Penney (1996):

$$a(v) = \partial V / \partial d \cdot v \quad (2)$$

where: $a(v)$: acceleration (m/s²); V : speed (m/s); d : distance (m)

The solution of Equation (2) provides the vehicle's speed profile as a function of distance traveled. This calculation is performed under impending skid conditions by continuously matching the required longitudinal friction (f_{Tdem}) to the roadway's available friction (f_{max}) and adjusting the horsepower utilization factor (n) from Equation (1) accordingly.

During tractive motion, the vehicle always accelerates, though the rate of acceleration decreases as speed increases. When $n < 100\%$, the vehicle operates at the friction limit, meaning any increase in power would cause skidding. Once n reaches 100%, the vehicle becomes power-limited: it continues to accelerate, but at a progressively lower rate, and acceleration diminishes more rapidly. Beyond this point, the vehicle is no longer constrained by impending skid conditions.

The model's outputs were validated in Mavromatis et al. (2023) by comparing field-measured acceleration profiles of the passing vehicle with the corresponding predictions of the vehicle dynamics model, demonstrating strong agreement. The vehicle parameters adopted in that study were derived from a combination of manufacturer specifications and established literature sources.

By adopting this dynamic and physics-based approach, the proposed methodology provides a more accurate and reliable estimation of PSD requirements, better reflecting the variability observed in real traffic conditions and vehicle performance characteristics.

2.2. PSD Assessment

The analysis is intended to provide a tool for evaluating the passing process. Accordingly, the assessment focuses exclusively on the interaction between vehicle dynamics and road geometry, incorporating the decision passing distance. The process, considered under free-flow conditions, involves three vehicles: the passing vehicle, the vehicle being passed, and the opposing vehicle (Fig. 1). Each vehicle exhibits distinct motion characteristics, and the following assumptions and criteria were applied:

- the speed of all three vehicles never exceeds the posted speed of the roadway
- the motion of the passed vehicle is under steady state conditions with a speed value below the posted speed of the roadway, where this speed difference is termed as ΔV
- the motion of the opposing vehicle is also under steady state conditions with a speed value equivalent to the roadway’s posted speed
- the passing vehicle’s motion during the passing process is under acceleration mode; however, it’s initial speed value at the starting phase is set equivalent to the relevant speed of the passed vehicle and increasing continuously until the roadway’s posted speed is reached from which point beyond steady state conditions apply
- the headway (dist₁) between the passing (front bumper) and the of the passed (front bumper) vehicles at the starting phase of the passing process was assumed 15m [9.5m as referenced in [Llorca et al. (2013)] + 5.5m approximately for the passed vehicle’s length]
- the headway (dist₂) between the passing (front bumper) and the passed (front bumper) vehicles at the ending phase of the passing process was assumed 30m [24m as referenced in [Llorca et al. (2013)] + 6m approximately the passing vehicle length]
- the safety margin was set to the constant value of 100m, which actually can be interpreted as a safety margin of approximately 3.5 seconds for 100km/h speed

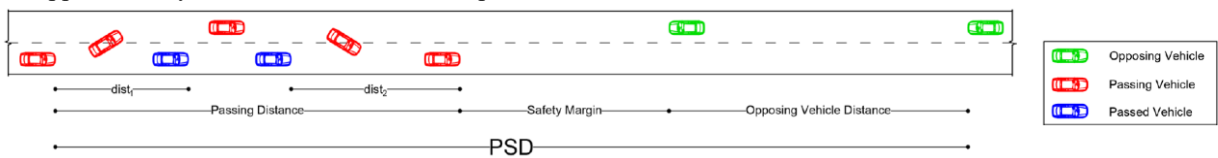


Fig. 1. Distance criteria utilized for PSD assessment.

A graphical representation of the calculated PSD assessment is presented in Fig. 2, which also includes, on a secondary vertical axis, the speed and horse power utilization [(n (%))] profiles of the passing vehicle.

Specifically, Fig.2 depicts the evolution of time vs distance for all three vehicles throughout the passing maneuver on a 4% longitudinal grade. The posted speed is set at 90 km/h, while both the speed of the passed vehicle and the initial speed of the passing vehicle are assumed to be 70 km/h ($\Delta V = 20$ km/h). The passing vehicle is characterized by an engine power of $P=120$ hp and is assumed to accelerate continuously until it reaches the posted speed, where it can be seen that the vehicle utilizes full horse-power prior to attaining the target speed. Consequently, the distance–time trajectory of the passing vehicle exhibits a pronounced non-linear behavior up to the point where the posted speed is reached, reflecting its dynamic acceleration characteristics. At $t=0$ s, the initial spacing between the passing vehicle (red line) and the passed vehicle (blue line) is defined as $dist_1$. The maneuver is considered complete when the passing vehicle attains a forward clearance of $dist_2$ relative to the passed vehicle. By additionally incorporating a 100 m safety margin at this stage, the required passing sight distance is estimated at 575 m, based on a linear extrapolation derived from the steady-state slope of the opposing vehicle’s distance–time profile.

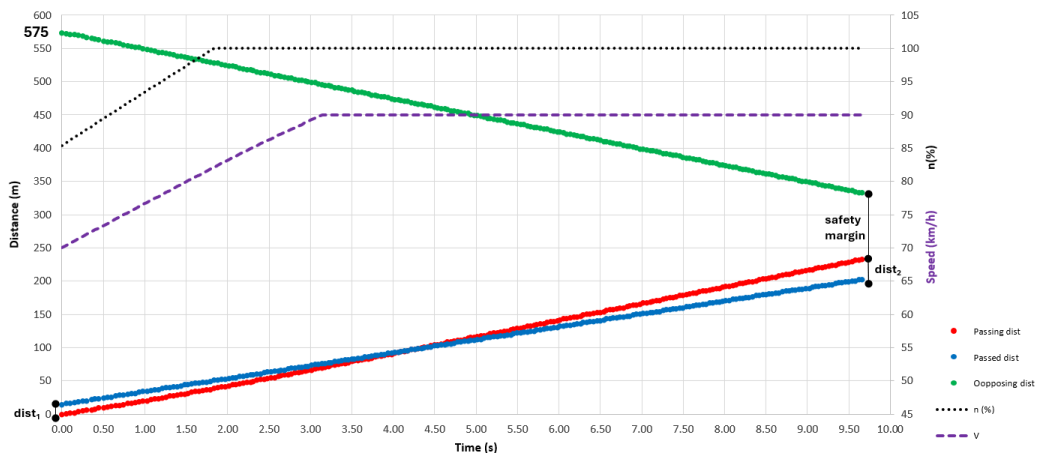


Fig. 2. PSD for $V_{\text{speed limit}} = 90$ km/h ($P=120$ hp, $\Delta V=20$ km/h, $s=4\%$).

3. Analysis

3.1. Lognormal Regression Modelling of PSD

The specification of the required PSD model was determined on the basis of a thorough descriptive analysis of the data revealing nonlinear associations of PSD with the examined variables (Equation 3). Consequently, with X_i the explanatory variables, β_i parameters to be estimated and ε_i the normally distributed $\sim [0, \sigma^2]$ error term, this lognormal model is formed as follows:

$$\log(\text{PSD}_i) = \sum \beta_i \cdot X_i + \varepsilon_i \quad (3)$$

The parameter estimates of the best fitting model (Equation 4) are presented in Table 1.

$$\log(\text{PSD}) = 14.8757 - 2.4750 \log(V_{\text{posted}}) + 14.3207 \text{hp}^{-1} + 0.000194 s^3 + 0.0364 V_0 \quad (4)$$

The regression dataset was generated from combinations of the four key explanatory variables considered in the PSD assessment. Posted speed (V_{posted}) ranged from 80 to 110 km/h, passed vehicle speed (V_0) from 70 to 100 km/h, engine power (hp) from 80 to 120 hp and roadway grade (s) from 1% to 6%. The resulting database consisted of 162 PSD observations obtained through repeated executions of the validated vehicle dynamics model, thus covering a broad range of realistic operating conditions encountered on two-lane rural roads.

In this case, this model can be analyzed, based on variables and interactions for all the examined alignments (e.g. $\log(V_{\text{posted}})$, hp^{-1} , s^3 , V_0), where $V_{\text{posted}} = V_0 + \Delta V$. Furthermore, best subsets regression was utilized to identify the optimal model according to the adjusted R-squared criterion. Multicollinearity was assessed using Variance Inflation Factors (VIFs). As shown in Table 1, the model exhibits a high adjusted R^2 and low VIF values (<2.00), indicating satisfactory explanatory capability and absence of concerning multicollinearity.

Tab. 1. Parameter Estimates of the Lognormal Regression Model of PSD

Parameter	B	Std. Error	t-value	p-value	VIF
(Intercept)	14.8757	0.2942	50.5636	<0.001	-
$\log(V_{\text{posted}})$	-2.475	0.072	-34.3889	<0.001	1.86
hp^{-1}	14.3207	3.1961	4.4807	<0.001	1.08
s^3	0.000194	0.000072	2.6993	0.0077	1.06
V_0	0.0364	0.0008	48.4234	<0.001	1.79
Adjusted R-squared	0.9364	df	4		

The relatively high adjusted R^2 value indicates strong explanatory capability and satisfactory predictive performance within the investigated parameter ranges. Nevertheless, the developed regression model should be interpreted as a practical engineering tool derived from simulated passing scenarios generated by the validated vehicle dynamics framework. Consequently, caution is required when extrapolating beyond the examined ranges of speed, horsepower and roadway grade conditions, and additional validation under different roadway and vehicle environments would be beneficial.

3.2. Sensitivity Analysis

To further assess the consistency of the regression results, a scenario-based sensitivity analysis was performed using the fitted equations of the developed models. One explanatory variable was varied over its observed range, while the remaining predictors were fixed at representative median values corresponding to realistic operating conditions ($V_{\text{posted}} = 100$ km/h, $\text{hp} = 100$, $s = 3.5\%$, $V_0 = 80$ km/h), approximately representing the central tendency of the examined dataset. The resulting plots (Figure 3) confirmed that the predicted trends were consistent with the signs and relative influence of the estimated regression coefficients. The analysis further indicated that speed-related variables (V_0 and V_{posted}) exert the strongest influence on the predicted PSD, dominating the model response across the examined range. In contrast, the remaining variables contribute to the overall behavior but play a comparatively less decisive role. In particular, the effect of s becomes more pronounced at higher values due to its cubic transformation (s^3), indicating that becomes significant primarily at higher slopes

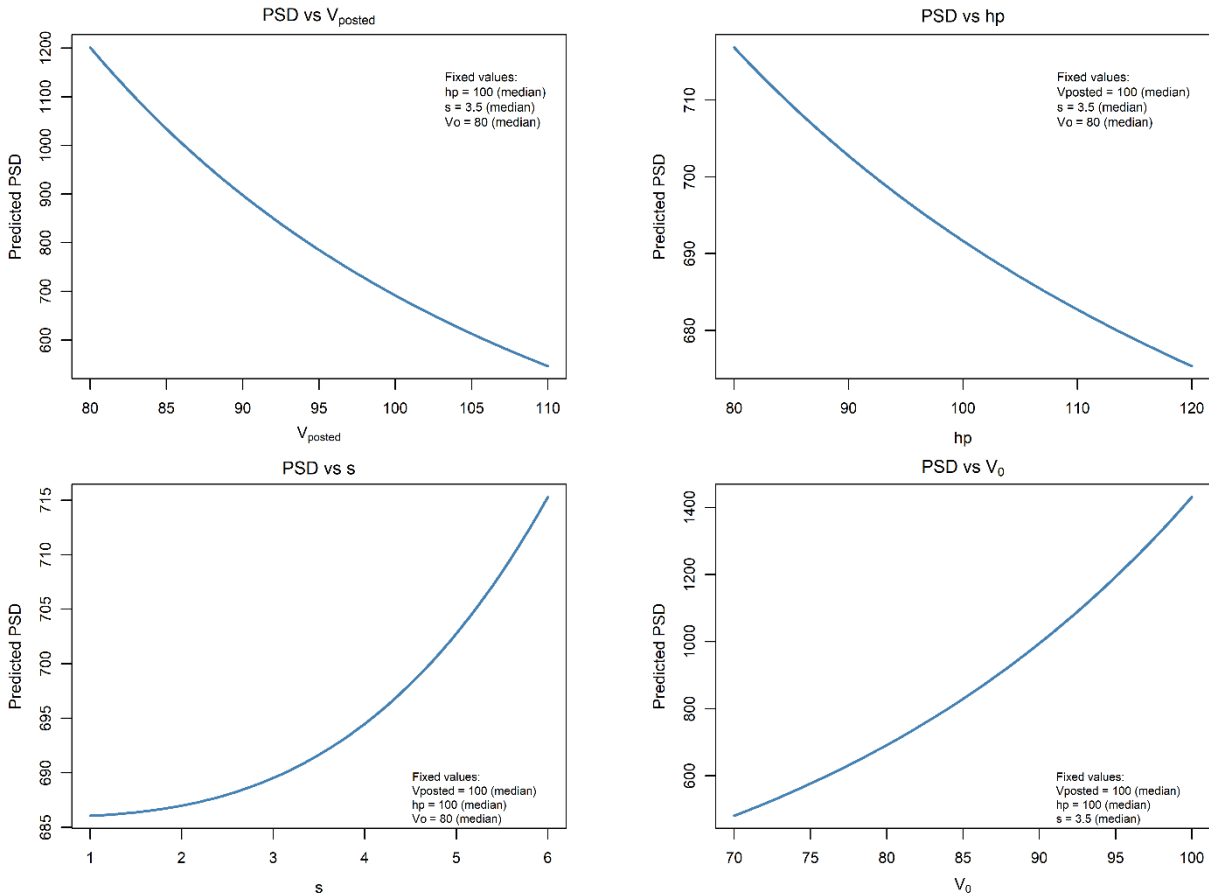


Fig. 3. Scenario-based sensitivity analysis diagrams.

4. Discussion and Conclusions

The present study investigates the interaction between vehicle dynamic characteristics and roadway geometry during the passing process. Passing sight distance (PSD) was evaluated with respect to roadway posted speed and the capability of the passing vehicle to safely complete the maneuver. This work constitutes an initial framework toward the standardization of the passing process, with potential applications in Advanced Driver Assistance Systems (ADAS). However, the current approach remains at a preliminary stage, as both passing and passed vehicle speeds were assumed constant, traffic conditions were considered free-flow, and fixed safety margins were adopted. These assumptions simplify the passing process and may not fully capture the variability observed under real-world traffic conditions.

Although the analytical formulation provides accurate PSD estimates, its computational complexity motivated the development of a statistical modeling approach. A regression-based model was formulated using four key vehicle–roadway variables with very satisfactory precision. The proposed models may support both researchers and practitioners in estimating PSD and defining passing zones based on the interaction between roadway and vehicle parameters.

The analysis indicated that speed-related variables, namely posted speed and the speed of the passed vehicle, exert the strongest influence on PSD. In contrast, the individual contribution of horsepower and slope was found to be comparatively moderate within the examined range. Nevertheless, the effect of slope becomes increasingly significant at higher values due to its cubic transformation (s^3).

Future research should focus on improving the representation of real driving conditions, including variable speeds and non-ideal traffic environments. Although the underlying vehicle dynamics model has previously been validated against field-measured acceleration profiles (Mavromatis et al., 2023), additional validation of the complete PSD assessment framework against observed real-world passing maneuvers obtained from naturalistic driving studies or field experiments would further strengthen the applicability of the proposed methodology. The integration of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication may enable the proposed methodology to operate as a real-time decision support tool. In future ADAS and connected vehicle environments, continuously updated information regarding vehicle position, speed, acceleration capability and available sight distance could be combined with the developed PSD models to provide passing advisories or warning messages, thereby enhancing safety during overtaking maneuvers.

Given that only a partial range of passenger cars was examined, further assessment is required to incorporate the entire vehicle fleet (SUVs, sport vehicles, heavy vehicles, etc.) as well as their related parameters.

In parallel, the impact of road geometry in terms of curvature (both horizontal and vertical), as well as operational capacity aspects are also challenging fields.

Finally, it is important to consider the impact of the human factor during the acceleration phase, as driver behavior may impose additional constraints on the passing process and ultimately affect overall vehicle safety performance.

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