TRB ANNUAL MEETING 2020
99th Annual Meeting
Washington, D.C.
January 12–16, 2020

Passing Sight Distance Assessment through the Interaction of Road – Vehicle Parameters

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Introduction

Two lane rural roads have the **highest** proportion of accidents. In terms of accident severity, accidents associated with failure during the passing process, such as head-on collisions or collisions between the passing and the passed vehicle driving in the same direction, seem to prevail.

Road sections with limited passing opportunities besides **safety** impose also **operational degradation**. Such cases might motivate certain drivers to make risky passing attempts either late in a passing zone or on a portion of the road not intended for passing and therefore seem mostly critical.

Objectives

The technological advancements provided by connected vehicles (CVs) and autonomous vehicles (AVs) are paving the way for a more “tailored” interaction between vehicle(s) and road environment. At present, vehicles equipped with Level 2 automation (partial automation) as defined by the society of automotive engineers (SAE) are already in the market, although mainly their contribution is limited to controlled conditions such as rather smooth geometric design.

In view of the deployment of such advanced driver assistance systems (ADAS) in the near future, the objective of the paper is to **investigate** the **interaction between vehicle dynamic parameters and road geometry** during the passing process.

The authors deliver passing distance outcomes as a function of critical vehicle and road parameters by **analyzing** the **ability** of the examined vehicle to **perform passing maneuvers**, where as a more generic outcome, **statistical models** for predicting PSDs are developed.

Methodology

The proposed PSD investigation is based on a safe and realistic representation of the **passing process** on tangent road sections, where the actual capacity of the passing vehicle to perform a passing maneuver was examined.

A previous vehicle dynamics model developed by the authors was utilized where all forces and moments applied to the vehicle were analyzed into a moving three dimensional coordinate system, formed by the vehicle’s longitudinal (X), lateral (Y) and vertical (Z) axis respectively. Through these axes, the influence of certain vehicle technical characteristics, road geometry and tire friction were expressed such as: vehicle speed/ wheel drive/ sprung and unsprung mass and it’s position of gravity center/ aerodynamic drag/ vertical lift/ track width/ wheel-base/ roll center/ suspension roll stiffness/ cornering stiffness/ grade/ superelevation rate/ rolling resistance tire-road adhesion values and horsepower supply.

Vehicle acceleration, which in the present analysis is not considered constant, was associated to the available horsepower rate on the wheels through the **horsepower utilization factor** “n” (%) since a vehicle cannot always be driven at full horsepower rate.

The analysis aims to deliver a tool for standardizing the passing process in view of the continuously evolving **ADAS** on vehicles. Therefore, the assessment of the vehicles’ passing process was investigated solely through the interaction between vehicle dynamics and road geometry, where decision passing distance was incorporated. The process, assuming free flow conditions, involves the contribution of three vehicles; namely the passing vehicle, the passed vehicle and the opposing vehicle.

All three vehicles have different motion characteristics, where based on relevant research the following criteria - assumptions were applied (Figure 1):

- 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
- energy deficits at the driven axle (94% approximately of the nominal value) combined with vehicle aging as well as the ability of the driver to perform by utilizing the maximum permissible horsepower rates reduce the available net engine horsepower; however such reduction (more than 10% in total) was disregarded and the nominal horsepower supply of the vehicle was assumed be equivalent to the one utilized
- the headway ($dist_1$) between the passing (front area) and the of the passed (front area) vehicles at the starting phase of the passing process was assumed 15m [9.5m + 5.5m approximately for the passed vehicle’s length]
- the headway ($dist_2$) between the passing (front area) and the passed (front area) vehicles at the ending phase of the passing process was assumed 30m [24m + 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 3.5seconds for 100km/h speed

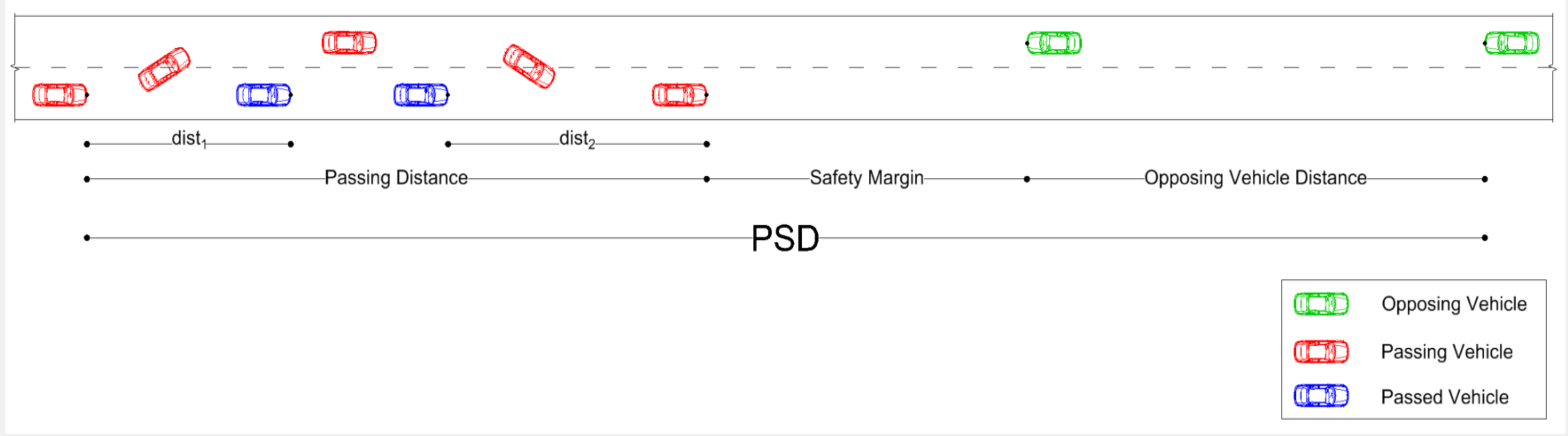

Figure 1 Distance criteria utilized for PSD determination

Field Measurements

The field measurements were carried out on two mild graded (1.00% and 2.00%) 2-lane rural road sections located at Spata area (near Athens) for both directions of travel. The recording device used for the **speed-distance data** was the Vericom VC4000 accelerometer. The **peak friction** supply for the examined road section was measured under dry road surface conditions f_{MAX}=0.82.

The key concept of the approach was the flexibility and the ease of the measuring process keeping it as **cost effective** as possible. Therefore, a HD machine-vision camera was utilized, mounted on the passing vehicle and recording continuously the passed vehicle during the maneuver. By that means, the distance among the two vehicles may be estimated for every successive frame, utilizing a typical image-based camera localization method that exploits tracked image features. The overall robustness of this single camera approach was ensured by an accurate camera pre-calibration step, along with an a-priori 3D photogrammetric reconstruction of several signalized targets (coded targets) mounted on the passed vehicle surface (Figure 2). The achieved localization accuracy σ is directly related to the distance (dist) from the camera towards the target-vehicle and ranges from some millimeters at close distances (dist < 5m), to several centimeters at longer distances (e.g. σ = ±10cm for dist > 10m).

Figure 3 illustrates the process for the utilized time frame of 0.50sec (Δt=0.50sec). The relative distance D traveled during the timeframe of Δt (between ti and ti+Δt) can be calculated from the distances between the passing and the passed vehicles, where having in mind their accelerating and steady state motion respectively, the following equations apply:

$$D = dist_{t=t_i} + V_{o,passed}\Delta t = dist_{t=t_i+\Delta t} + V_{o,passing(t=t_i)}\Delta t + \frac{1}{2}a_i\Delta t^2 \qquad (1)$$

$$V_{o,passing(t=t_i+\Delta t)} = V_{o,passing(t=t_i)} + a_i\Delta t \qquad (2)$$

where:
a_i: instant passing vehicle acceleration (m/sec^2)
$V_{o,passed}$: constant speed of the passed vehicle (m/sec)
$V_{o,passing}$: initial speed of the passing vehicle [t=0: $V_{o,passing}$= $V_{o,passed}$] (m/sec)

From Equation 1 the **instant acceleration a_i** can be defined. By substituting a_i in Equation 2, the speed $V_{o,passing(t=ti+\Delta t)}$ of the passing vehicle at the ending (beginning) of time frame ti (ti+Δt) can be calculated. However, the achieved accuracies of distance measurements, (given estimation) though sufficient for close distances, yield inaccurate estimations of speed and acceleration at somewhat longer distances

Figure 2 Coded targets mounted on the passed vehicle surface

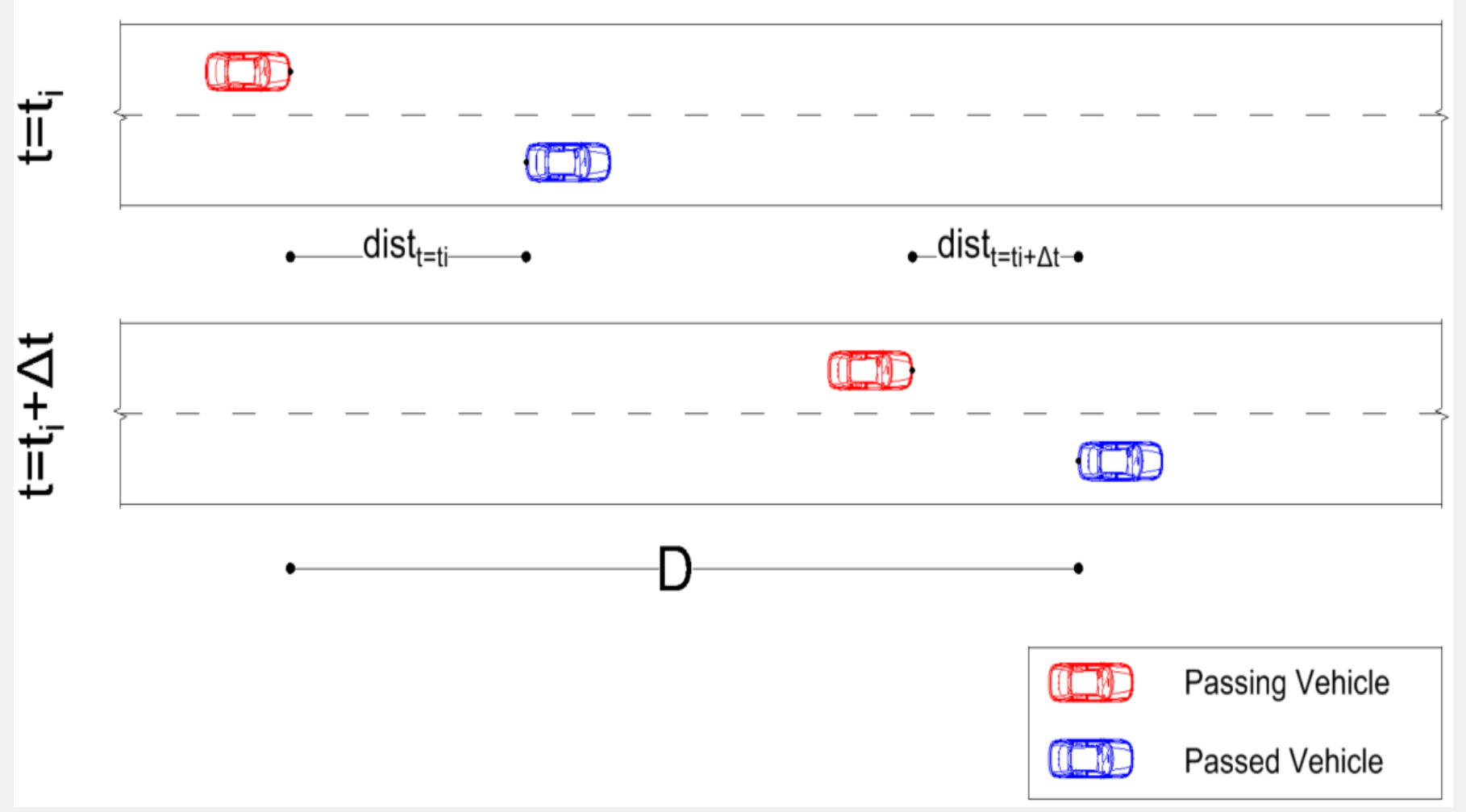

Figure 3 Relative positions of the passing and the passed vehicles for Δt=0.5sec

Therefore, the validation of the passing process was limited in correlating the **passing vehicle’s motion** under acceleration between field data and the outputs of the vehicle dynamics model. Since the speed of the passed vehicle is considered constant, once the performance under acceleration of the passing vehicle is known, the relative distance between the passing and the passed vehicle can be easily figured out. The validation was performed by correlating the acceleration performance of B Class (Toyota Yaris Diesel, **manual gear**) and C Class (Toyota CH-R, **automatic transmission**) passenger cars against the vehicle dynamics model (Figure 4).

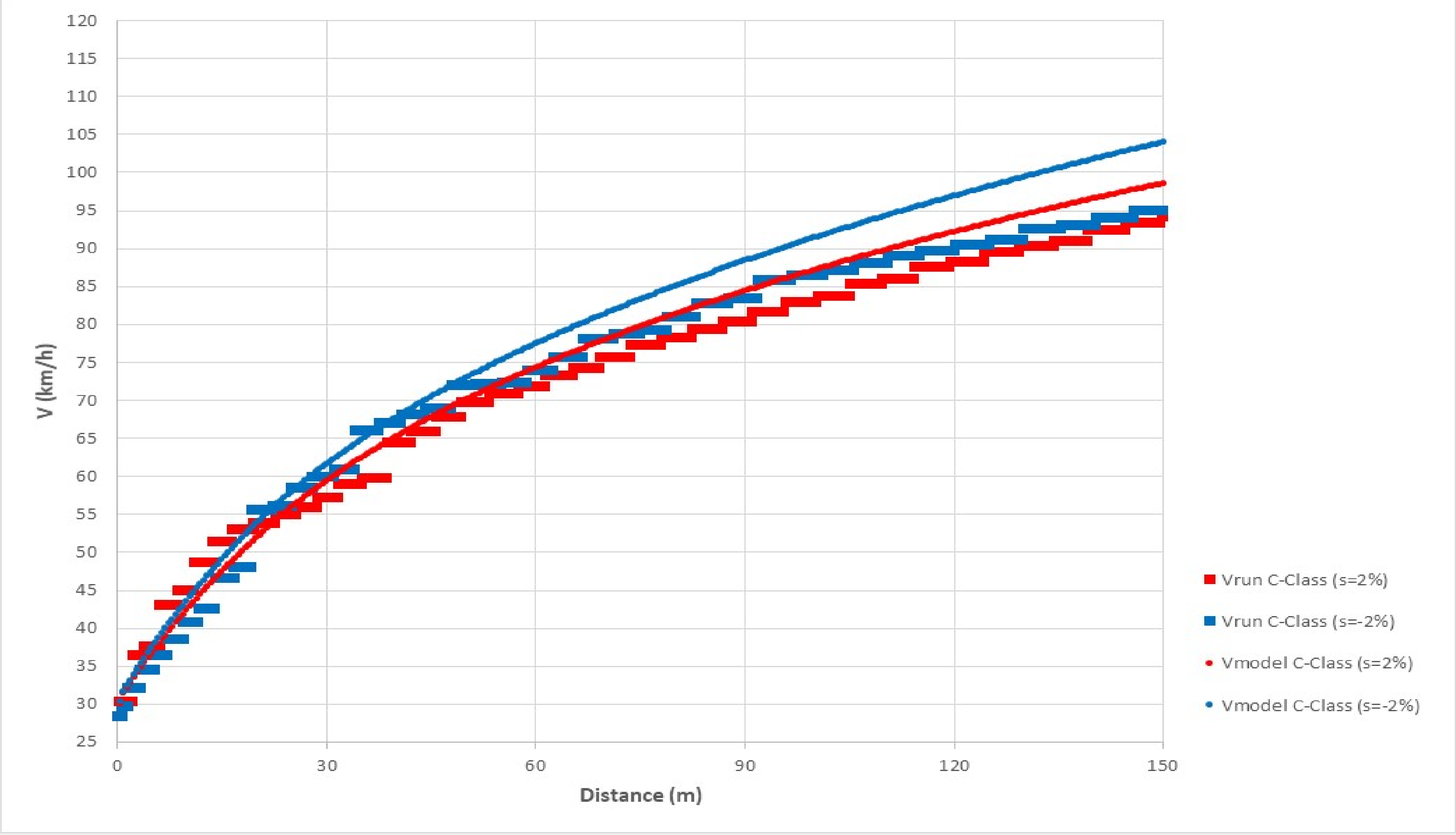

Figure 4 Acceleration Performance Correlation [automatic transmission (Vo=28.5km/h P=122hp)

in general the assessed speed distance correlation, especially for the automatic transmission vehicle, were found satisfactory, having in mind that optimum vehicle handling was assumed (human factor ignored).

Analysis

Aiming to utilize a **uniform** approach for assessing PSDs, the current analysis was performed in line with the German rural road design guidelines (RAL, 2012) and more specifically for EKL2 and EKL3 design classes where the design – posted speed values are set to 100km/h and 90km/h respectively. In RAL, 2012 design guidelines, PSD is dependent on the homogeneity of the proposed road design classes and no longer on speed (PSD=600m).

Certain cases by design class were examined by arranging the combinations of 4 independent variables; namely:

- vehicle horsepower rates [P (hp)], (80hp, 100hp, 120hp)
- difference between passed vehicle’s speed (also initial speed of passing vehicle) and roadway’s posted – design speed [ΔV (km/h)], (10km/h, 20km/h, 30km/h)
- peak friction supply coefficients [fmax], (0.35, 0.50, 0.65)
- grade values [s (%)], (max. upgrade, level and max. downgrade)

Every independent variable came along with 3 different values, where in total, **81 different scenarios** per design class were examined. The developed PSD graphs delivered various interesting findings although some of them can be reached rather straightforward. As expected, the **dominant parameter** that mostly affected PSD was found to be the **speed differential parameter ΔV**. Figure 5 illustrates the interaction of the remaining independent variables on PSD by retaining the roadway’s friction value, where it can be seen that the sum of the passing maneuver under both acceleration and posted speed status deliver the passing zone per examined case.

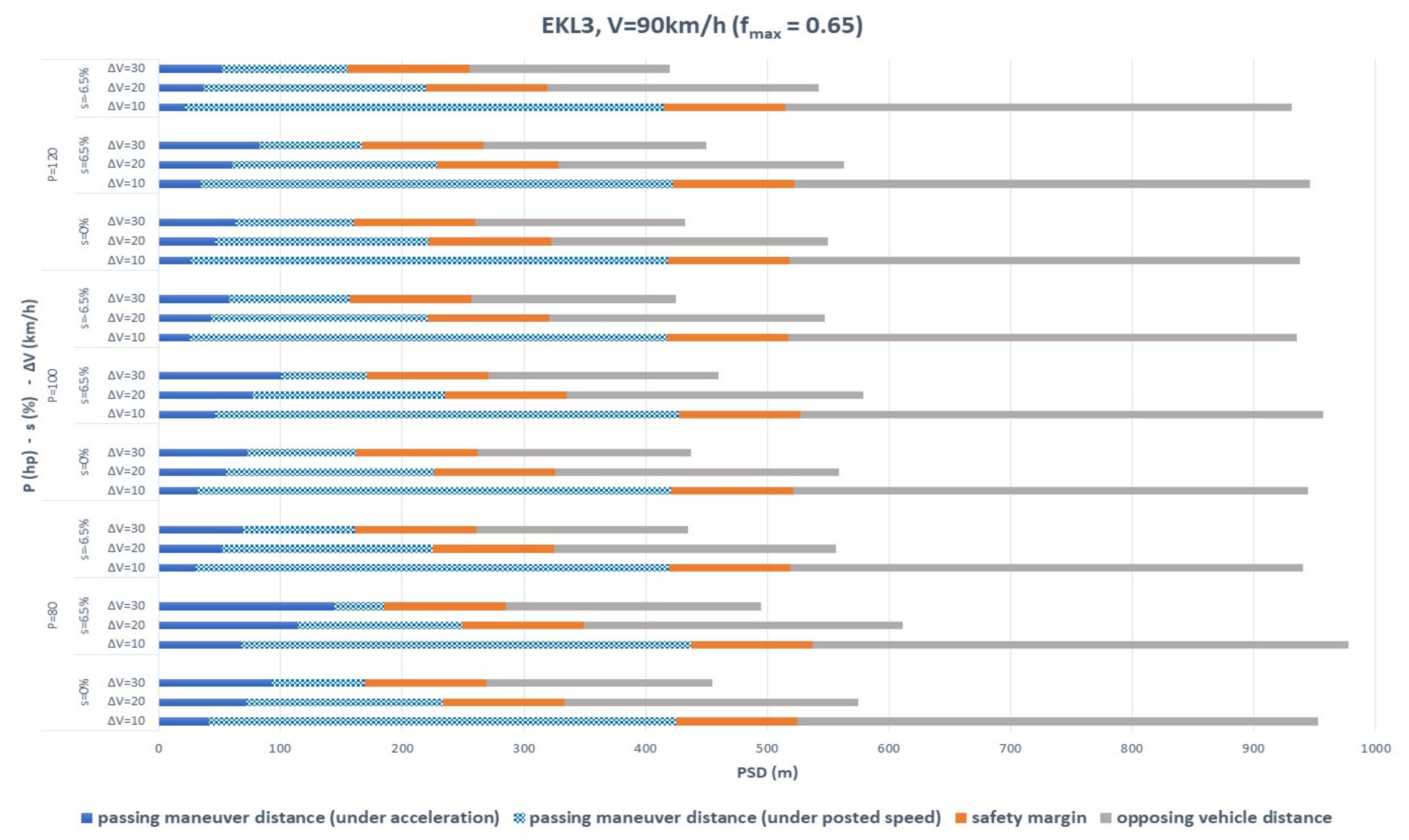

Figure 5 Interaction of Road - Vehicle Parameters during PSD Determination (EKL3, V=90km/h, f_{max}=0.65)

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. A histogram of the response variable led to the identification of a clearly skewed density function, suggesting a **lognormal distribution**. The parameter estimates and goodness-of-fit measures of the best fitting model are presented in Table 1.

TABLE 1 (a,b) Parameter estimates and goodness-of-fit of the lognormal regression model of PSD

(a) EKL2

Parameter	**B**	**Std. Error**	**t-value**	**p-value**
(Intercept)	3.19150	0.01520	209.949	**<0.001**
ΔV	-0.01555	0.00043	-35.750	**<0.001**
P f_{max}	-0.00070	0.00024	-2.949	**0.004**
s ΔV	0.00018	0.00004	4.808	**<0.001**
Null Log-likelihood		48.947		
Final Log-likelihood		166.033		
Likelihood Ratio Test		2.443		
df		3		
Adjusted R-squared		**0.942**		

(b) EKL3

Parameter	**B**	**Std. Error**	**t-value**	**p-value**
(Intercept)	3.15000	0.01532	205.567	**<0.001**
ΔV	-0.01560	0.00044	-35.588	**<0.001**
P f_{max}	-0.00072	0.00024	-3.006	**0.0035**
s ΔV	0.00015	0.00003	4.775	**<0.001**
Null Log-likelihood		48.641		
Final Log-likelihood		165.389		
Likelihood Ratio Test		2.448		
df		3		
Adjusted R-squared		**0.944**		

Conclusions

The present paper investigated the interaction between vehicle dynamic parameters and road geometry during the passing process. Passing distance data were delivered with respect to the roadway’s posted speed as well as the ability of the examined (passing) vehicle to perform such maneuvers. The assessment is an **opening paradigm** of how the passing process can be standardized and therefore deployed in existing ADAS. At present time this effort is at preliminary stage since the speeds of the passed and the passing vehicles were considered constant but also traffic conditions were assumed ideal (free flow).

Although the impact of (standing alone) vehicle horsepower rates (at least the examined values) on the passing process was rather moderate, the speed difference (ΔV) between the passed vehicle and the posted speed value was found to impact excessively PSD (>600m), especially for ΔV<20km/h. In every case, further research is necessary to quantify more accurately the amount of utilized horsepower rates during passing maneuvers.

A related issue of great importance to be further investigated, mainly for ΔV=10km/h, is the **potential impact** on the **roadway’s operational level**, since unless the vehicle to be passed further decreases it’s speed, the roadway is subject to perform below the designed level of service. Therefore, in partial automation environment (e.g. Level 2), the required PSDs are not expected to reduce. In more advanced V2V automation environment, such a reduction seems feasible; however, the vehicles interaction necessitates deeper investigation.