

1 **PASSING SIGHT DISTANCE ASSESSMENT**
2 **THROUGH THE INTERACTION**
3 **OF ROAD – VEHICLE PARAMETERS**
4

5
6 Stergios Mavromatis, Assistant Professor
7 School of Civil Engineering
8 National Technical University of Athens, Greece, GR-15773
9 e-mail: stemavro@central.ntua.gr
10

11 Vassilios Matragos, PhD Candidate
12 School of Civil Engineering
13 National Technical University of Athens, Greece, GR-15773
14 e-mail: vasmatragos@mail.ntua.gr
15

16 Rania Liza, Researcher
17 School of Civil Engineering
18 National Technical University of Athens, Greece, GR-15773
19 e-mail: ranialz.rl@mail.ntua.gr
20

21 Konstantinos Apostoleris,
22 School of Rural and Surveying Engineering
23 National Technical University of Athens, Greece, GR-15773
24 e-mail: kapostol@central.ntua.gr
25

26 Lazaros Grammatikopoulos, Assistant Professor
27 School of Surveying & Geoinformatics Engineering
28 University of West Attica, Athens, Greece, GR-12210
29 e-mail: lazaros@uniwa.gr
30

31 George Yannis, Professor
32 School of Civil Engineering
33 National Technical University of Athens, Greece, GR-15773
34 e-mail: geyannis@central.ntua.gr
35

36
37
38
39
40
41
42
43
44
45
46 Word Count: 6500 words + 4 tables (250 words per table) = 7500 words
47

48
49 Submitted to the Transportation Research Board, August 2019

1 **ABSTRACT**

2 This paper investigates the interaction between vehicle dynamics parameters and road
3 geometry during the passing process. The methodology is based on a realistic representation of the
4 passing task with respect to roadway's posted speed and the ability of the passing (examined)
5 vehicle to perform such maneuvers. Regarding passing distance outputs, an existing vehicle
6 dynamics model was utilized, where aiming to assess the model's accuracy, instrumented field
7 measurements were performed.

8 The analytical model is computationally demanding. Therefore statistical models were
9 worked out, in line with the German rural road design guidelines, to determine passing sight
10 distances (PSDs) by arranging combinations of 4 critical vehicle – roadway parameters; namely
11 vehicle horsepower rates, variations between the passed vehicle's speed and roadway's posted
12 speed, peak friction supply coefficients and grade values. The analysis revealed that the difference
13 between the speed of the passed vehicle and the posted speed value, as well as certain interactions
14 of the assessed parameters impact excessively PSD, especially for values below 20km/h.

15 The lognormal modelling approach for predicting PSDs was found efficient and may be
16 useful to researchers and practitioners aiming to evaluate the interaction of the utilized road –
17 vehicle parameters in terms of determining PSDs as well as passing zones.

18 Although more advanced communication between vehicles or between vehicles and road
19 environment seems a prerequisite in order integrated guidance during passing maneuvers to be
20 enabled, the present research consists an opening paradigm of how the passing process can be
21 standardized and therefore deployed in advanced driver assistance systems (ADAS).

22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

1 INTRODUCTION AND PROBLEM STATEMENT

2 Two lane rural roads have the highest proportion of accidents (1). In terms of accident
3 severity, accidents associated with failure during the passing process, such as head-on collisions
4 or collisions between the passing and the passed vehicle driving in the same direction, seem to
5 prevail (e.g. 2, 3, 4, 5).

6 Passing is permissible on specific road areas (passing zones). The locations with passing
7 zones strongly depend on the provision of at least minimum sight distance [passing sight distance
8 (PSD)]. PSD is the distance that drivers must be able to see along the road ahead to safely and
9 efficiently initiate and complete passing maneuvers of slower vehicles on two-lane rural roads
10 using the lane normally reserved for opposing traffic (6).

11 Road sections with limited passing opportunities besides safety impose also operational
12 degradation. Such cases might motivate certain drivers to make risky passing attempts either late
13 in a passing zone or on a portion of the road not intended for passing and therefore seem mostly
14 critical (7).

15 The most effective mean to eliminate such accidents is to provide additional passing lanes,
16 or at least protected passing zones through the provision of continuous 3-lane cross-section (2+1
17 roads). However, such arrangements are not possible for every road environment due to economic,
18 topographical or environmental protection constraints (8). Therefore, PSD is a vital design
19 element, which directly imposes economic as well as safety and operational considerations.

20 A wide number of research related to the passing process can be found in the literature and
21 many models relating the involved parameters have been calibrated. In many of them passing
22 maneuver data were collected either through an instrumented vehicle, which represented the
23 passing vehicle (e.g. 9, 10), or from video recording (e.g. 11, 12, 13), where the overall aim was
24 to assess the relevant distance, time and speed parameters. Some authors utilized driving
25 simulators as well in order to support their findings (e.g. 7, 14). The advantage of driving
26 simulators experiments, besides providing demographic information of the drivers (e.g. 15, 16), is
27 that such assessments deliver very accurate data related to the passing task (14).

28 In terms of modelling passing zones and PSDs, although most of the relevant research
29 studies have reported numerous interesting results, due to the disparity of the directly involved
30 parameters, the proposed passing distance values are extracted based on rather critical assumptions
31 and therefore should be treated with caution. For example, in many studies the speed of the passing
32 vehicle, or the speed differential between the passing and the passed vehicle is considered constant,
33 where in others, acceleration data, although not at all easy to measure, are considered stable as
34 well or in some cases assessed through the measured passing time. The same applies in current
35 road design practice, where many assumptions are being adopted as well.

36 In AASTHO (17) design guidelines, PSD is based on field observations and expressed as
37 the outcome of four different distance components, namely;

- 38 • d_1 , distance traveled during perception and reaction time and initial acceleration
- 39 • d_2 , distance traveled while the passing vehicle occupies the left lane
- 40 • d_3 , distance between passing and opposing vehicle at the end of the maneuver (safety
41 margin)
- 42 • d_4 , distance traveled by an opposing vehicle ($2/3$ of d_2)

43 The adopted PSD values (Table 1) are based on certain combinations of “assumed” speeds between
44 the passing and the passed vehicle utilizing a speed differential of 19km/h (12mph).

45
46

1

Table 1 PSD values for two lane rural roads (AASHTO, 2018)

Design Speed (km/h)	Assumed Speeds (km/h)		PSD (m)
	Passed Vehicle	Passing Vehicle	
50	31	50	160
60	41	60	180
70	51	70	210
80	61	80	245
90	71	90	280
100	81	100	320

2

3

4

5

6

7

8

9

In the German RAL, 2012 design guidelines (18), PSD depends on the homogeneity of the proposed road design classes and no longer on speed, where as a result the required PSD is set to 600m. This value of 600m has evolved from the PSD requirement of a passenger car at 100km/h attempting to perform a passing maneuver to a truck driven at 70km/h, while at the same time, at the opposing traffic stream, another passenger car is running at 100km/h. The required PSD is the sum of the distances covered by the two passenger cars plus a safety margin distance of 100m.

10

11

12

13

14

15

16

17

Safety during the passing process can be violated by many means. Besides operational constraints imposed from traffic volumes and/or traffic composition, the impact of short passing zones, although not extensively validated by accident data seems to be very important in terms of smooth vs violent return of the passing vehicle to the through lane. A recent study (19) showed that in short passing zones, 92% of passing maneuvers ended beyond the passing zone, compared to 21% of longer passing zones (over 300 m). A similar research (20) revealed that the proportion of forced and violent returns for 270m long passing zone was 10%, and it increased to 45% at 200m long passing zone. Another issue of concern is that in many research studies (e.g. 7, 21); the speeds of passing vehicles were found to be over the posted speed limit.

18

19

20

21

22

From the above it is more than evident that the passing process is a complex task, where the recommendations provided from the existing analyses unavoidably are rather widespread. At the same time, it is widely accepted that the conventional approach for improving safety seems to be constantly moving towards the benefits of automation.

23

24

25

26

27

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, (22)] are already in the market, although mainly their contribution is limited to controlled conditions such as rather smooth geometric design (23).

28

29

30

31

32

33

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 intend to 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.

34

METHODOLOGY

35

36

37

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.

38

39

The ability of a vehicle to accelerate has already been addressed in previous research of the authors (24-26) where aiming to assess vehicle safety from the interaction between road geometry,

1 tire - pavement friction and vehicle parameters a vehicle dynamics model was developed. More
2 specifically, vehicle acceleration, among other parameters, was associated to the available
3 horsepower rate on the wheels through the horsepower utilization factor “n” (%) since a vehicle
4 cannot always be driven at full horsepower rate.

5 The following sub-section provides a brief discussion on how the model was structured,
6 where more details regarding the full equations description are available through references
7 (24-26).

8 It is worth mentioning that in the vehicle’s dynamics model and of course within the present
9 analysis, the acceleration is not considered constant.

11 **Vehicle Dynamics Approach**

12 All forces and moments applied to the vehicle were analyzed into a moving
13 three-dimensional coordinate system, coinciding at the vehicle gravity center and formed by the
14 vehicle’s longitudinal (X), lateral (Y) and vertical (Z). Through these axes, the impact of certain
15 vehicle technical characteristics, road geometry and tire friction were expressed, such as vehicle
16 speed/ wheel drive/ sprung and unsprung mass and it’s position of gravity center/ aerodynamic
17 drag/ vertical lift/ track width/ wheel-base/ roll center/ suspension roll stiffness/ cornering
18 stiffness/ grade/ superelevation rate/ rolling resistance tire-road adhesion values and horsepower
19 supply.

20 Moreover, the model takes into account variables related to vehicle steering and tire
21 sideslip angles (27), the actual wheel load due to the lateral load transfer as well as the
22 corresponding alteration of the lateral force on each wheel, thus creating a four-wheel vehicle
23 dynamics modelling (27-29). The model’s outputs were validated against the known data derived
24 by two other distinct cases: the final climbing speed of a truck travelling on a grade (30) and the
25 output data from the well-known CARSIM Simulation Software (31). Both cases revealed a
26 satisfying match.

27 The available tractive effort of the vehicle (driving force minus rolling resistance) acting
28 on the front or rear axle (depending on the driving configuration) was associated to the vehicle’s
29 speed as well as the net power available at the driving wheels. Since a vehicle cannot always be
30 driven at 100% of its available horsepower rate, the horsepower utilization factor (n) was
31 introduced and the following equation applies:

$$32 \quad F_x = 745.60 \frac{P}{v} \frac{n}{100} \quad (1)$$

34 where :

35 F_x : tractive force (Nt)

36 P : net engine horsepower available at the driven axle [around 94% of the nominal value, (32)]
37 (hp)

38 v : vehicle speed (m/sec)

39 n : horsepower utilization factor (%)

40
41 By applying laws of mechanics, the vehicle’s instant acceleration, which is expressed as a
42 four-degree polynomial equation, can be formed as a function of vehicle’s instant speed as well as
43 driven distance, thus delivering the following differential equation which is resolved by utilizing
44 numerical Runge-Kutta method (33):

$$45 \quad a(v) = \frac{dv}{dd} v \quad (2)$$

1 where:
2 $a(v)$: acceleration (m/sec^2)
3 v : speed (m/sec)
4 d : distance (m)
5

6 The solution of Equation (2) delivers the vehicle speed variation as a function of the
7 required distance. This procedure takes place at impending skid conditions by pairing the
8 determined demanded longitudinal friction (f_{Tdem}) to the provided friction supply of the roadway
9 and adapting each time the horsepower utilization factor n from Equation (1).

10 It is evident that during vehicle's tractive mode, irrespective of whether the vehicle utilizes
11 or not the total net engine horsepower ($n=100\%$, or $n<100\%$), the vehicle increases the speed,
12 which means that acceleration rate decreases.

13 As long as the vehicle utilizes part of the total net engine horsepower ($n<100\%$), the vehicle
14 is driven at impending skid conditions, since any increase of "n" will deliver vehicle skidding.

15 However, when $n=100\%$, although the vehicle cannot utilize additional horsepower, the
16 speed of the vehicle continues to increase due to acceleration presence, but at a lower rate, since
17 the total amount of available horsepower is continuously utilized. For the same reason, the
18 acceleration drops more rapidly. From that point on, the vehicle is no longer driven at impending
19 skid.

20 The above can be seen through Figure 1, where the accelerating performance of a C-class
21 passenger car (KIA Proceed) as a function of the driven distance is shown. Regarding the utilized
22 vehicle parameters (Table 2, second column), although an effort was made to provide them from
23 the vehicle industry (bolded values), most of them were taken from the literature (28). The engine
24 horsepower was assumed to be 80hp for the above run.

25 The initial speed of the vehicle was assumed $V_o=80\text{km}/\text{h}$, the friction supply was set to the
26 unfavorable value of $f_{Tmax}=0.35$, and the road gradient was assumed 5.50% upgrade. The
27 breakpoint in terms of distance travelled, where the vehicle reaches 100% horsepower utilization
28 (red line) is shown through a dashed vertical line (distance=68m). It can be seen that prior to that
29 point the vehicle was accelerating at impending skid conditions (orange line with $f_{Tdem}=0.35$),
30 where beyond 68m from the starting point of the assessment, the vehicle speed and acceleration
31 continue growing and reducing respectively with evidently different rates.

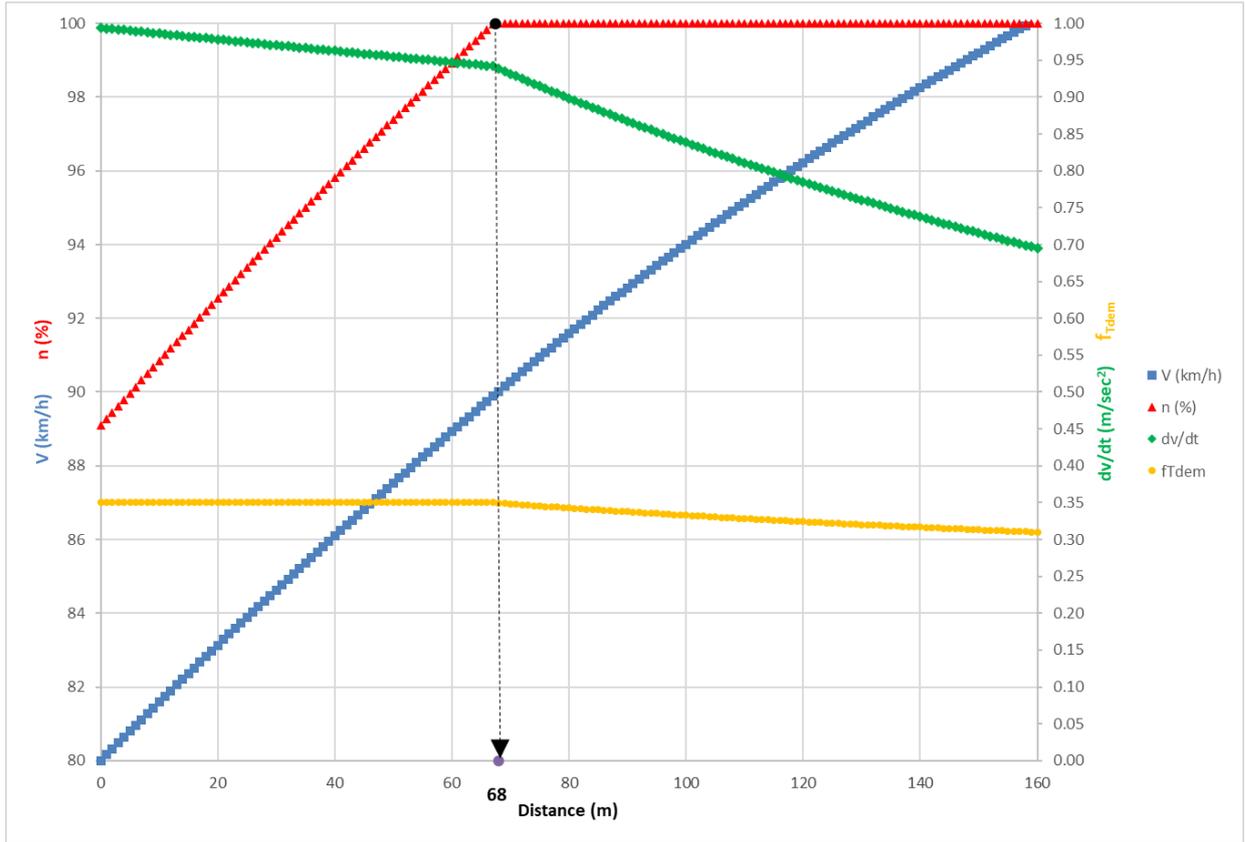


FIGURE 1 Speed - Horsepower Utilization and Acceleration – Friction Variation vs Distance ($V_0=80\text{km/h}$, $P=80\text{hp}$, $s=5.50\%$, $f_{Tmax}=0.35$)

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20
- 21
- 22
- 23
- 24

1
2
3

TABLE 2 Vehicle Parameters Inserted to the Model

NOTE: The Parameters in Bold Refer to the Vehicle's Manual.

	C Class KIA Proceed	C Class Toyota CH-R	B Class Toyota Yaris	
L (m)	2.650	2.640	2.510	Wheelbase
t _f (m)	1.538	1.550	1.470	Front track width
t _r (m)	1.536	1.570	1.460	Rear track width
m (kgr)	1300	1500	1150	Vehicle mass
l _f (m)	1.161	1.161	1.031	Position of GC from front
h (m)	0.620	0.620	0.610	Position of GC from surface
K _{qf} (Nm/rad)	27502	27502	19882	Suspension roll stiffness
K _{qr} (Nm/rad)	14324	14324	9282	Suspension roll stiffness
C _{af} (kp/rad)	2295.7	2295.7	2867.1	Cornering coef. (front)
C _{ar} (kp/rad)	2120.7	2120.7	2316.8	Cornering coef. (rear)
m _{uf} (kgr)	92	92	80	Unsprung mass (front)
m _{ur} (kgr)	120	120	72	Unsprung mass (rear)
h _{Rf} (m)	0.020	0.020	0.190	Roll center height (front)
h _{Rr} (m)	0.410	0.410	0.190	Roll center height (rear)
r _{dyn} (m)	0.290	0.290	0.260	Dynamic radius
A _f (m ²)	1.850	1.850	1.750	Frontal area
c _N	0.28	0.28	0.31	Lift drag
c _d	0.33	0.32	0.30	Aerodynamic drag
P (hp)	100	120	90	Horsepower

4

5 PSD Assessment

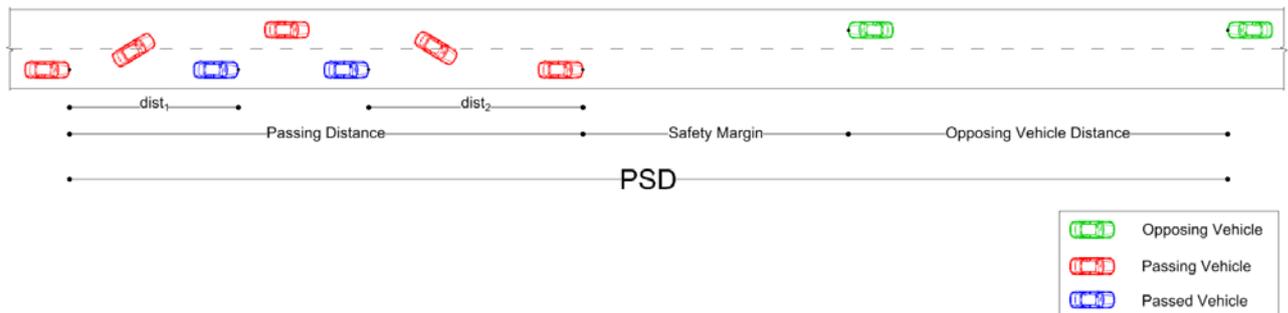
6 The analysis aims to deliver a tool for standardizing the passing process in view of the
7 continuously evolving ADAS on vehicles. Therefore, the assessment of the vehicles' passing
8 process was investigated solely through the interaction between vehicle dynamics and road
9 geometry, where decision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

12 All three vehicles have different motion characteristics, where the following criteria -
13 assumptions were applied:

- 14 • the speed of all three vehicles never exceeds the posted speed of the roadway
- 15 • the motion of the passed vehicle is under steady state conditions with a speed value below
16 the posted speed of the roadway, where this speed difference is termed as ΔV
- 17 • the motion of the opposing vehicle is also under steady state conditions with a speed value
18 equivalent to the roadway's posted speed
- 19 • the passing vehicle's motion during the passing process is under acceleration mode;
20 however, it's initial speed value at the starting phase is set equivalent to the relevant speed
21 of the passed vehicle and increasing continuously until the roadway's posted speed is
22 reached from which point beyond steady state conditions apply

- 1 • energy deficits at the driven axle (94% approximately of the nominal value, as already
2 mentioned) combined with vehicle aging as well as the ability of the driver to perform by
3 utilizing the maximum permissible horsepower rates reduce the available net engine
4 horsepower; however such reduction (more than 10% in total) was disregarded and the
5 nominal horsepower supply of the vehicle was assumed be equivalent to the one utilized
- 6 • the headway ($dist_1$) between the passing (front area) and the of the passed (front area)
7 vehicles at the starting phase of the passing process was assumed 15m [9.5m as referenced
8 in (10) + 5.5m approximately for the passed vehicle's length]
- 9 • the headway ($dist_2$) between the passing (front area) and the passed (front area) vehicles at
10 the ending phase of the passing process was assumed 30m [24m as referenced in (10) + 6m
11 approximately the passing vehicle length]
- 12 • the safety margin was set to the constant value of 100m (18), which actually can be
13 interpreted as a safety margin of approximately 3.5seconds for 100km/h speed

14 The above mentioned distance criteria of the passing process are shown in Figure 2.
15



16 **FIGURE 2 Distance Criteria Utilized for PSD Determination**
17
18

19 Field Measurements - Validation

20 The field measurements were carried out on two mild graded (1.00% and 2.00%) 2-lane
21 rural road sections located at Spata area (near Athens) for both directions of travel. The recording
22 device used for the speed-distance data was the Vericom VC4000 accelerometer (34). The peak
23 friction supply for the examined road section was measured under dry road surface conditions
24 $f_{MAX}=0.82$. More information regarding both speed-distance and friction recording procedures
25 through the accelerometer, can be found in a similar research of the authors (26).

26 Due to the fact that the opposing vehicle's speed as well as the safety margin were
27 considered constant for the same roadway, the validation of the process was concentrated in
28 assessing the passing distance between the passing and the passed vehicles.

29 The key concept of the approach was the flexibility and the ease of the measuring process
30 keeping it as cost effective as possible. Therefore, a HD machine-vision camera was utilized,
31 mounted on the passing vehicle and recording continuously the passed vehicle during the
32 maneuver. By that means, the distance among the two vehicles may be estimated for every
33 successive frame, utilizing a typical image-based camera localization method that exploits tracked
34 image features.

1 The overall robustness of this single camera approach was ensured by an accurate camera
 2 pre-calibration step, along with an a-priori 3D photogrammetric reconstruction of several
 3 signalized targets (coded targets) mounted on the passed vehicle surface as seen through Figure 3.
 4 The achieved localization accuracy σ is directly related to the distance (dist) from the camera
 5 towards the target-vehicle and ranges from some millimeters at close distances (dist < 5m), to
 6 several centimeters at longer distances (e.g. $\sigma = \pm 10\text{cm}$ for dist > 10m).
 7



8
 9
 10 **FIGURE 3 Coded Targets Mounted on the Passed Vehicle Surface**
 11
 12

13 Figure 4 illustrates the process for the utilized time frame of 0.50sec ($\Delta t = 0.50\text{sec}$). The
 14 relative distance D traveled during the timeframe of Δt (between t_i and $t_i + \Delta t$) can be calculated
 15 from the distances between the passing and the passed vehicles, where having in mind their
 16 accelerating and steady state motion respectively, the following equations apply:
 17

$$18 \quad D = \text{dist}_{t=t_i} + V_{o,\text{passed}}\Delta t = \text{dist}_{t=t_i+\Delta t} + V_{o,\text{passing}(t=t_i)}\Delta t + \frac{1}{2}a_i\Delta t^2 \quad (3)$$

$$19 \quad V_{o,\text{passing}(t=t_i+\Delta t)} = V_{o,\text{passing}(t=t_i)} + a_i(t_i + \Delta t)^2 \quad (4)$$

20 where:

21 a_i : instant passing vehicle acceleration (m/sec^2)

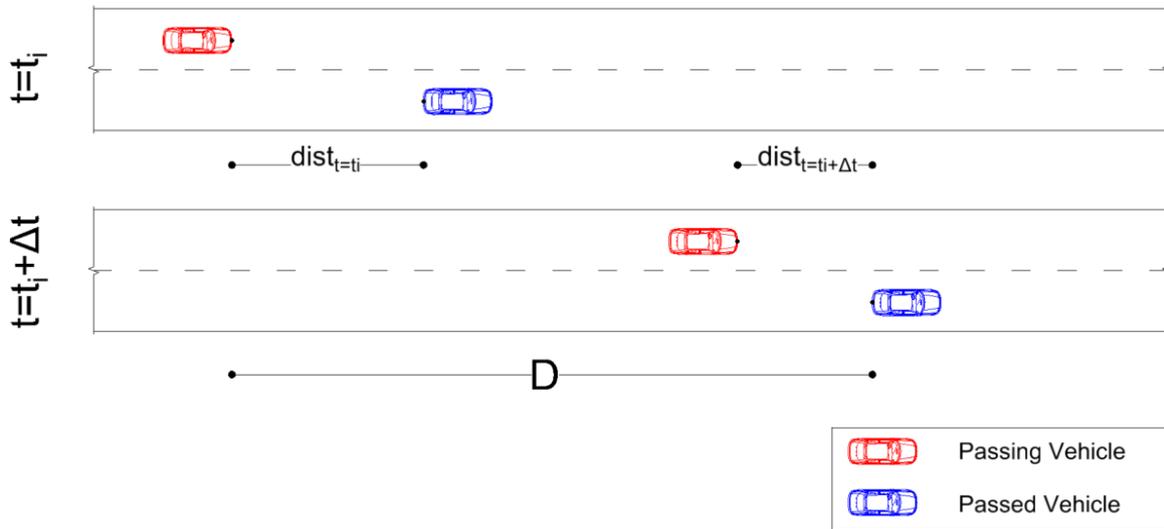
22 $V_{o,\text{passed}}$: constant speed of the passed vehicle (m/sec)

23 $V_{o,\text{passing}}$: initial speed of the passing vehicle [$t=0$: $V_{o,\text{passing}} = V_{o,\text{passed}}$] (m/sec)
 24

25 From Equation 3 the instant acceleration a_i can be defined. By substituting a_i in Equation
 26 4, the speed $V_{o,\text{passing}(t=t_i+\Delta t)}$ of the passing vehicle at the ending (beginning) of time frame t_i ($t_i + \Delta t$)
 27 can be calculated. However, the achieved accuracies of distance measurements, (given estimation)
 28 though sufficient for close distances, yield inaccurate estimations of speed and acceleration at
 29 somewhat longer distances.

30 Nevertheless, the exploitation of Computer Vision techniques based on camera recordings
 31 remains a critical issue for speed estimation, in the sense that it can meet and exceed the accuracy
 32 demands of this approach. This is feasible by leveraging different camera configuration scenarios

1 and processing methods (e.g. synchronized recordings from multiple stationary and moving
 2 cameras, employment of a long-base stereo camera on board, integration of a visual system with
 3 data from various sensors such as Lidar, GPS/INS and Radar). In this context, it is worth
 4 mentioning that the case of simultaneous video recording from multiple cameras installed on the
 5 ground and on board of the vehicle, may yield an essential increase in the final accuracy of this
 6 approach. Hence, it could exceed significantly the corresponding results from single-device units
 7 such as single-camera monitoring systems or mobile mapping systems consisting of a single
 8 camera and Lidar sensor.

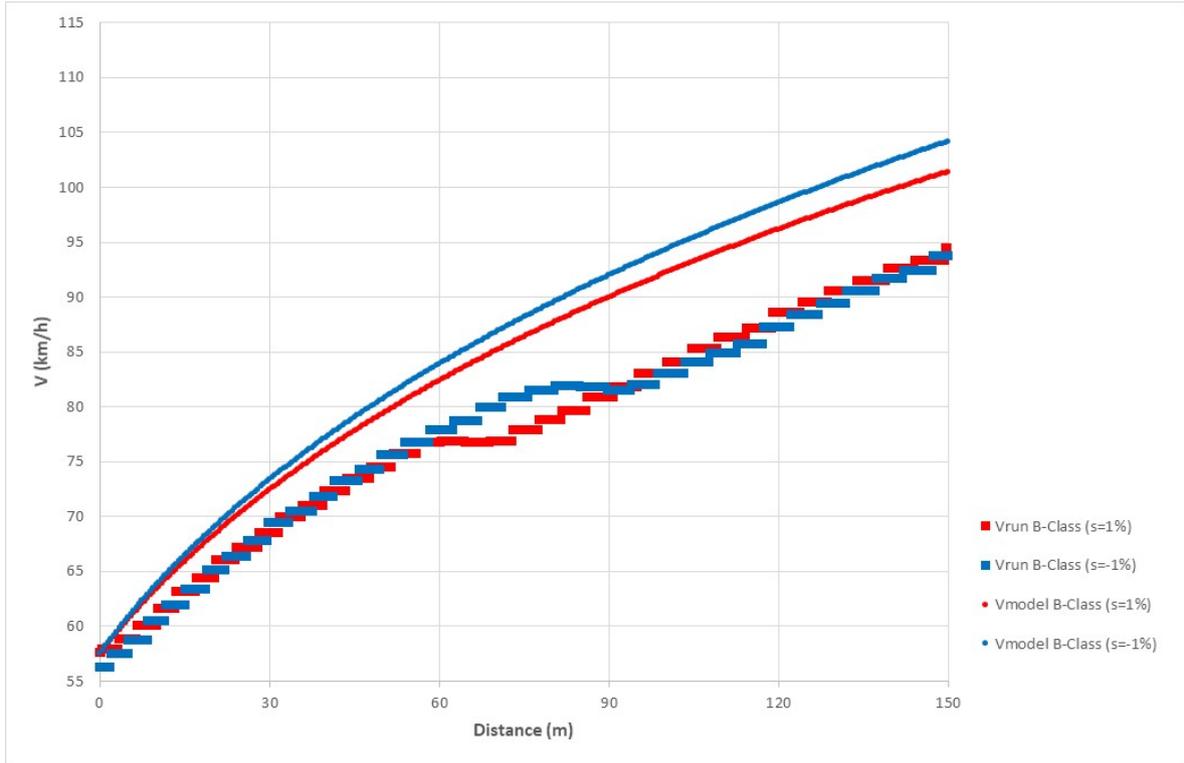


9
 10 **FIGURE 4 Relative positions of the passing and the passed vehicles for $\Delta t=0.5\text{sec}$**

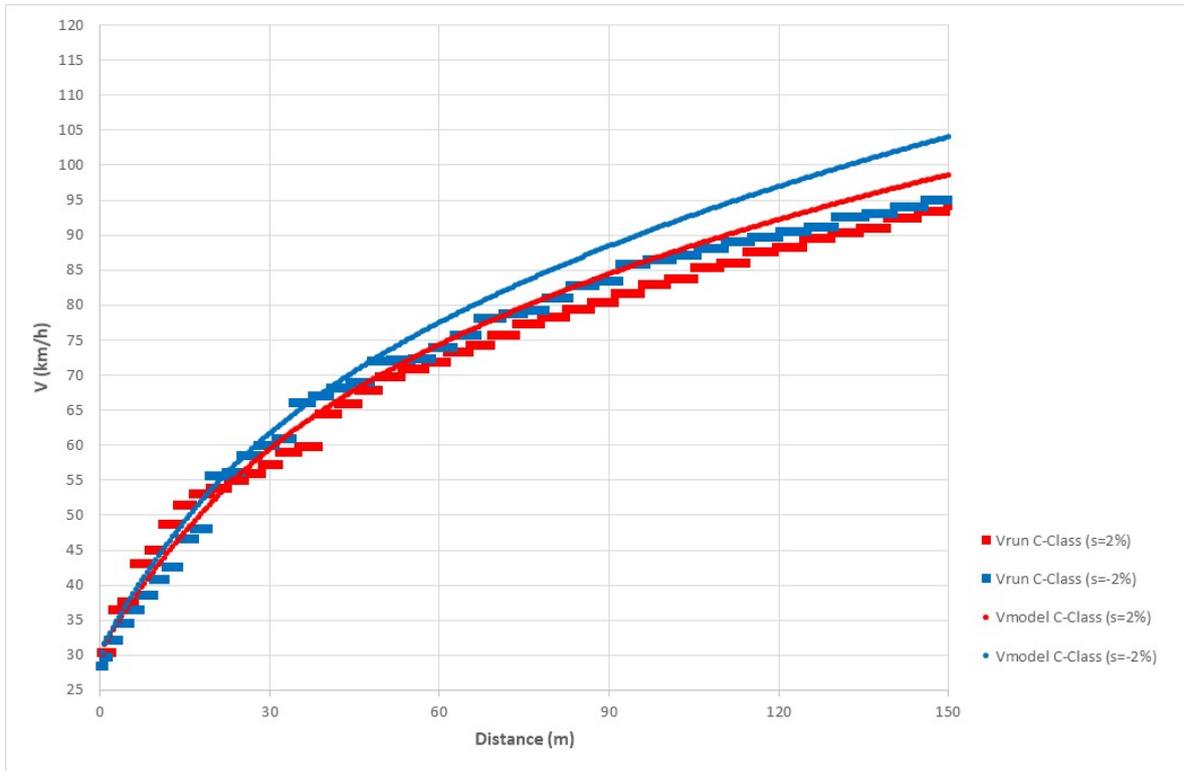
11
 12 Therefore, the validation of the passing process was limited in correlating the passing
 13 vehicle's motion under acceleration between field data and the outputs of the vehicle dynamics
 14 model. Since the speed of the passed vehicle is considered constant, once the performance under
 15 acceleration of the passing vehicle is known, the relative distance between the passing and the
 16 passed vehicle can be easily figured out.

17 The validation was performed by correlating the acceleration performance of B Class
 18 (7 year old Toyota Yaris Diesel, manual gear) and C Class (brand new Toyota CH-R, automatic
 19 transmission) passenger cars against the vehicle dynamics model. The utilized parameters by
 20 vehicle can be seen through Table 2, where the initial speed values (V_o , at steady state conditions)
 21 were engaged from the accelometer in order to avoid vehicle odometer errors. However, in order
 22 to take into consideration more realistic situations (vehicle aging, energy deficits), the applied
 23 horsepower rates differed slightly as follows: 80hp for Toyota Yaris (90hp x 90%) and 112hp for
 24 Toyota CH-R (120hp x 94%).

25 The results are shown through Figure 5(a,b), where it can be seen that the automatic
 26 transmission vehicle delivers a better fit against vehicle dynamics model outputs (Figure 5b). More
 27 specifically, in Figure 5a the gearshift area, approximately 70m from the starting point, generates
 28 a sort of delay in vehicle performance. However, in general the assessed speed distance correlation,
 29 especially for the automatic transmission vehicle, were found satisfactory, having in mind that
 30 optimum vehicle handling was assumed (human factor ignored).



(a) manual transmission ($V_0=57.5\text{km/h}$, $P=80\text{hp}$)



(b) automatic transmission ($V_0=28.5\text{km/h}$ $P=122\text{hp}$)

FIGURE 5 (a,b) Acceleration Performance Correlation between Field Data – Vehicle Dynamics Model

1
2
3

4
5
6
7

1 In every case, a more advanced photogrammetric-based validation process is necessary in
2 order to assess also potential impact from vehicle steering during the passing process, which within
3 the present analysis was ignored.

4 5 ANALYSIS

6 Aiming to utilize a uniform approach for assessing PSDs, the current analysis was performed
7 in line with the design classes of German (RAL, 2012) rural road design guidelines, where, as
8 already stated, PSD is currently dependent on the homogeneity of the proposed road design classes
9 and no longer on speed. The examined design classes as well as the utilized control values of
10 speed, grade and PSD requirements are shown in Table 3.

11
12 **Table 3 Control Values for RAL, 2012 (18)**

Design Class	Design Speed V (km/h)	Grade s (%)	PSD (m)
EKL2	100	5.50	600
EKL3	90	6.50	600

13
14 The proposed PSD assessment was implemented for EKL2 and EKL3 design classes with
15 posted speed values of 100km/h and 90km/h respectively. Moreover, the following parameters
16 from the vehicle - roadway interaction were used:

17 The vehicle nominal (also assumed as utilized) horsepower rate, where three different rates
18 were utilized: 80hp, 100hp and 120hp.

19 Pavement friction, where three values of peak friction supply coefficients f_{max} were used
20 (0.35, 0.50 and 0.65). Since the sliding friction coefficient and consequently the relevant peak
21 value are subject to excessive variations in terms of wet-dry pavement conditions, the intention
22 was to assess pavements with poor friction performance under both wet (0.35) and dry (0.65)
23 pavement conditions.

24 The potential grade impact during vehicle passing performance was also investigated. For
25 each design class, in accordance with Table 3, three different grade values were investigated (max.
26 upgrade, level and max. downgrade).

27 Finally, per examined design class, as the speed of the opposing vehicle was always set to
28 the value shown in Table 3, three different speed values for the passed vehicle were investigated;
29 namely, 10km/h, 20km/h and 30km/h below the respective design speed value.

30 Summarizing, certain cases by design class were examined by arranging the combinations
31 of the above mentioned 4 independent variables [vehicle horsepower rates (P), difference between
32 passed vehicle's speed (also initial speed of passing vehicle) and roadway's posted – design speed
33 (ΔV), peak friction supply coefficients (f_{max}), and grade values (s)]. Every independent variable
34 came along with 3 different values, where in total, 81 different cases per design class were
35 examined.

36 The developed PSD graphs delivered various interesting findings although some of them
37 can be reached rather straightforward.

38 As expected, the dominant parameter that mostly affected PSD was found to be the speed
39 differential parameter ΔV , where for all the examined cases, the analysis revealed that the passing
40 vehicle was able to reach the posted speed of the roadway.

1 When a vehicle with low horsepower rate is driven at impending skid conditions ($n < 100\%$),
2 the passing performance for a vehicle with the same initial road – vehicle parameters but with
3 greater horsepower rate remains the same.

4 In cases where a vehicle for a certain pavement friction outperforms (reaches 100% of its
5 nominal horsepower rate, $n = 100\%$) at the beginning of the passing process, even when the vehicle
6 performs on improved pavement, in terms of friction, the vehicle will still necessitate the same
7 PSD. An exception is noticed when the vehicle outperforms during the passing process.

8 Figure 6a and Figure 6b illustrate two distinctive cases; the interaction of the remaining
9 independent variables on PSD by retaining the roadway's grade and friction values respectively.

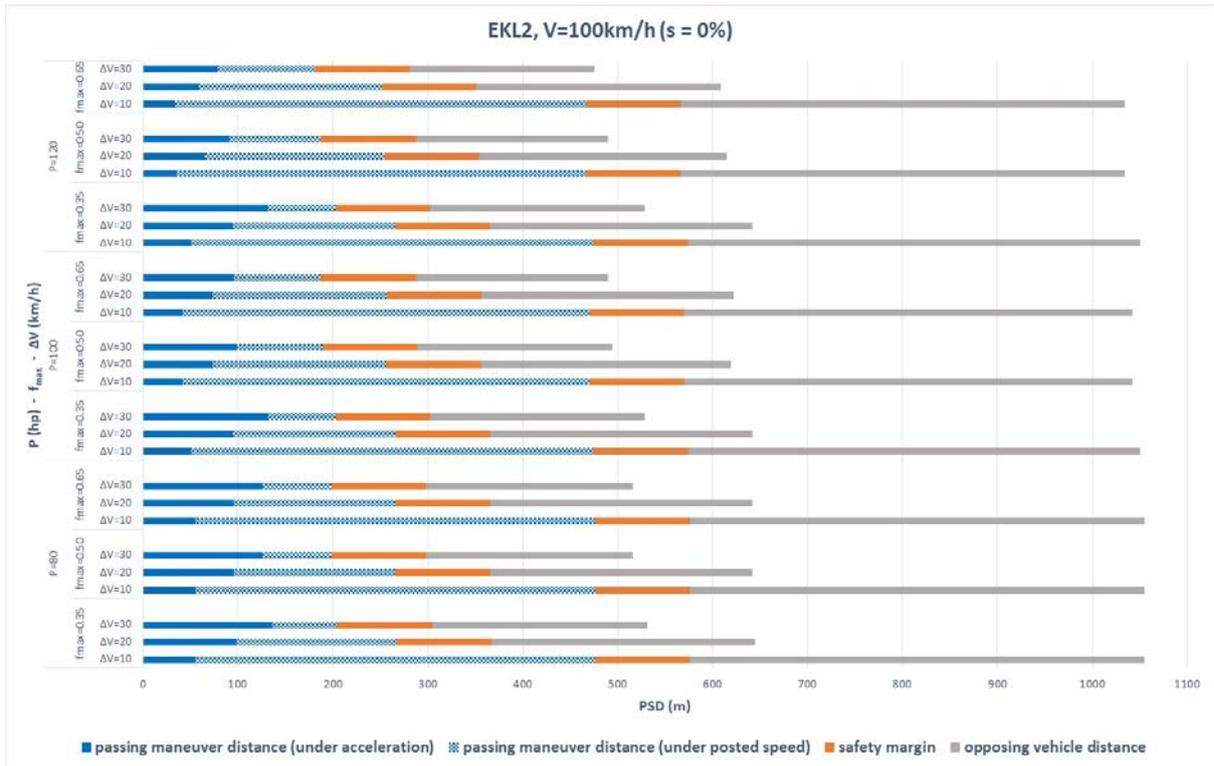
10 In Figure 6a, it can be seen that between the two extreme horsepower rates assessed, PSD
11 has a moderate difference of approximately 20m on the most favorable in terms of friction
12 pavement ($f_{\max} = 0.65$) which vanishes as f_{\max} decreases.

13 On the other hand, as seen through Figure 6b, the grade impact, between the two extreme
14 grade values assessed, is more noticeable on the vehicle with the lowest horsepower rate
15 (approximately 20m for $P = 120\text{hp}$ vs 35m for $P = 80\text{hp}$).

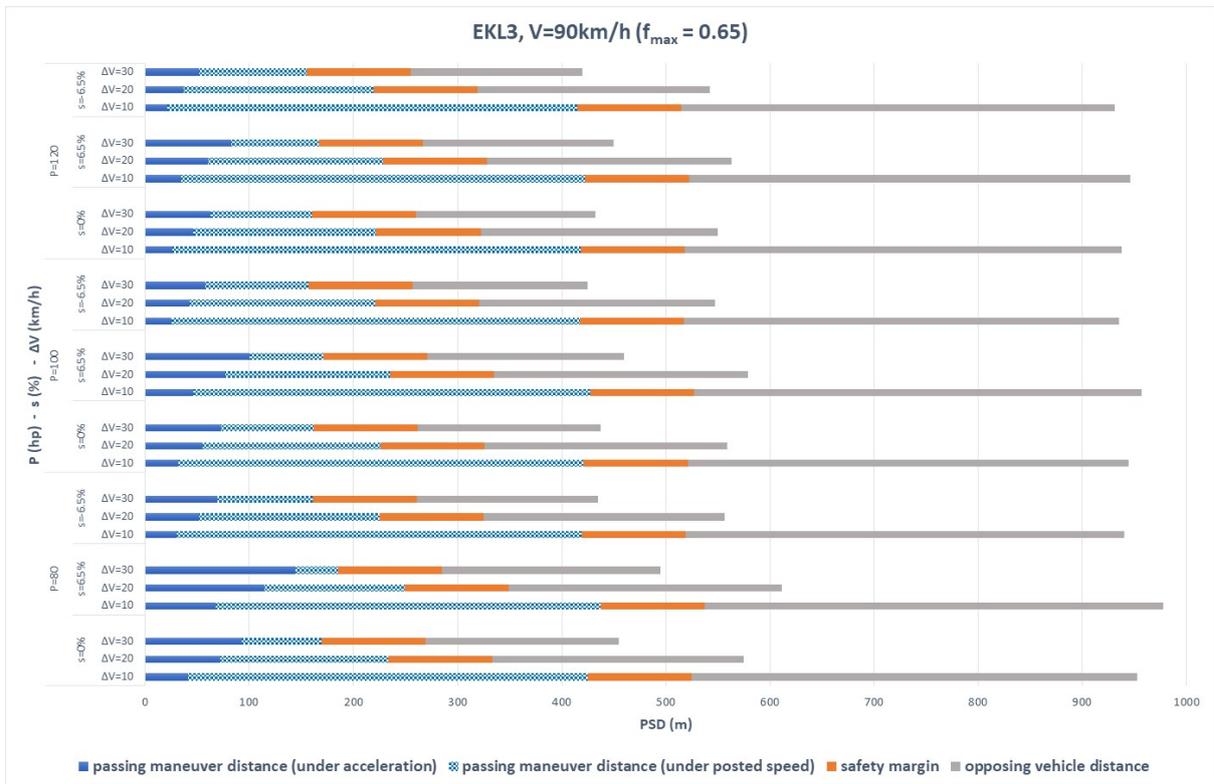
16 Among the most important findings is the fact that the passing process is not always
17 acceptable (600m PSD requirement exceeded). This is mostly evident for cases where the speed
18 of the passed vehicle is below 20km/h from the roadway's posted speed. Especially for EKL2
19 design class (Figure 6a), when ΔV was set to 20km/h, it was found that the demanded PSD slightly
20 exceeded 600m ($s = 0\%$).

21 Another interesting outcome is the fact that solely the examined horsepower supply of the
22 vehicles has a rather moderate impact on the final PSD. This is explained as follows; the vehicle
23 supplied with the higher horsepower rate reaches the posted speed travelling a shorter distance.
24 Comparing the two extreme cases of 80hp and 120hp, the vehicle equipped with 80hp travels
25 approximately 40% more distance (blue bars in Figure 6b) in order to reach the roadway's posted
26 speed. This means that when both vehicles reach the posted speed value, the 80hp vehicle,
27 compared to the passed vehicle has shorter relative distance to complete the passing maneuver
28 than the 120hp vehicle (varies approximately 10m – 30m, depending on grade and ΔV). As a
29 result, the passing maneuver distance per vehicle with 80hp and 120hp is somehow balanced.

30
31
32
33
34
35
36
37
38
39
40
41
42
43
44



(a) EKL2, V=100km/h, s=0%



(b) EKL3, V=90km/h, $f_{max}=0.65$

FIGURE 6 (a,b) Interaction of Road - Vehicle Parameters during PSD Determination

1
2
3

4
5
6

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. A histogram of the response variable led to the identification of a clearly skewed density function, suggesting a lognormal distribution (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 and goodness-of-fit measures of the best fitting model are presented in Table 4. The final model is specified for each examined road class (EKL2, EKL3) separately:

EKL2 Design Class:

$$\log(\text{PSD}) = 3.1915 - 0.01555 \text{ dV} - 0.0007 \text{ P } f_{\text{max}} + 0.00018 \text{ s dV} \quad (4)$$

EKL3 Design Class:

$$\log(\text{PSD}) = 3.1500 - 0.01560 \text{ dV} - 0.00072 \text{ P } f_{\text{max}} + 0.00015 \text{ s dV} \quad (5)$$

In this case, this model can be analyzed, based on variables and interactions for all the examined alignments (e.g. dV, P x f_{max} , s x dV). Furthermore, a quadratic function of gradient (s) and horsepower (P) was tested but was not found to outperform the logarithmic function with respect to PSD. A collinearity test was conducted, to ensure that the independent variables were not correlated with each other.

The parameter estimates of the main effects suggest that an increase in one interaction (e.g. s x dV) increase passing sight distance, while on others (e.g. dV, P x f_{max}) decrease PSD. The likelihood ratio test leads to accept the model compared to the null model, and an adjusted R-squared is equal to 0.94 in both cases, which is satisfactory.

A closer look at the predicted values suggest that the differences between observed and predicted values are low; however, the model residuals are not white noise (e.g. unrelated to the predicted values), and the plot of residuals against the predicted values suggests the presence of a more complex non-linear relationship.

1
2 **TABLE 4 (a,b) Parameter Estimates and Goodness-of-Fit of the Lognormal Regression**
3 **Model of PSD**

4 (a) EKL2

Parameter	B	Std. Error	t-value	p-value
(Intercept)	3.19150	0.01520	209.949	<0.001
dV	-0.01555	0.00043	-35.750	<0.001
P f _{max}	-0.00070	0.00024	-2.949	0.004
s dV	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		

5
6 (b) EKL3

Parameter	B	Std. Error	t-value	p-value
(Intercept)	3.15000	0.01532	205.567	<0.001
dV	-0.01560	0.00044	-35.588	<0.001
f _{Tmax} *Ph	-0.00072	0.00024	-3.006	0.00357
s* dV	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		

7
8 It is clear that the final model specification may not address all possible combinations of
9 design parameters with the same accuracy and the lognormal model is certainly an approximation.
10 However, even with this imperfect specification, the model can be useful within a preliminary
11 assessment of the design parameters as regards PSD.

12 **DISCUSSION AND CONCLUSIONS**

13
14 The present paper investigated the interaction between vehicle dynamic parameters and
15 road geometry during the passing process. Passing distance data were delivered with respect to the
16 roadway's posted speed as well as the ability of the examined (passing) vehicle to perform such
17 maneuvers.

18 The assessment is an opening paradigm of how the passing process can be standardized
19 and therefore deployed in existing ADAS. At present time this effort is at preliminary stage since
20 the speeds of the passed and the passing vehicles were considered constant but also traffic
21 conditions were assumed ideal (free flow).

22 An imminent challenge is to further improve the described methodology by enabling more
23 sophisticated communication between vehicles (V2V) or between vehicles and road environment
24 (V2I) and thus enable the utilization of guidance during the passing process in an advanced vehicle
25 automation levels environment. During such an effort, cases of unforeseen situations that might

1 cancel the passing process should be also addressed. Such cases, among others, include the
2 capability of obstacles detection on the roadway through cameras with deep learning process, tire
3 – road friction assessment due to harsh weather conditions, etc.

4 The analytical model, although delivers accurate passing distance outputs, especially for
5 automatic transmission vehicles, is computationally demanding and therefore a statistical
6 modelling approach was worked out by utilizing 4 vehicle – roadway variables with very
7 satisfactory precision. The derived models may be useful to researchers and practitioners aiming
8 to determine PSDs as well as passing zones by assessing the interaction of road – vehicle
9 parameters.

10 Although the impact of (standing alone) vehicle horsepower rates (at least the examined
11 values) on the passing process was rather moderate, the speed difference (ΔV) between the passed
12 vehicle and the posted speed value was found to impact excessively PSD, especially for
13 $\Delta V < 20$ km/h. In every case, further research is necessary to quantify more accurately the amount
14 of utilized horsepower rates during passing maneuvers.

15 A related issue of great importance to be further investigated, mainly for $\Delta V = 10$ km/h, is
16 the potential impact on the roadway's operational level, since unless the vehicle to be passed
17 further decreases its speed, the roadway is subject to perform below the designed level of service.

18 In addition, since only a partial range of passenger cars was examined, further investigation
19 is required to incorporate the entire vehicle fleet (SUVs, sport vehicles etc.) as well as their related
20 parameters.

21 Moreover, the impact of road geometry in terms of curvature (both horizontal and vertical)
22 as well as intersections areas are also challenging fields.

23 Concluding, it should not be ignored that the human factor during the acceleration process
24 might impose additional restrictions and, consequently, affect vehicle's safety performance.

25 26 REFERENCES

- 27 1. Federal Highway Administration FHWA. *Safety Effects of Horizontal Curve and Grade*
28 *Combinations on Rural Two-Lane Highways (FHWA-HRT-13-077)*. Office of Safety Research
29 and Development, VA, 2014.
- 30 2. Molinero, A., E. Carter, C. Naing, M. Simon, and T. Hermitte. Accident causation and pre-
31 accidental driving situations. Part 1. Overview and general statistics, *TRACE - Traffic Accident*
32 *Causation in Europe Report*. 2008.
- 33 3. Richter, T. and S. Ruhl. Untersuchung von Maßnahmen zur Prävention von Überholunfällen
34 auf einbahnigen Landstraßen, [Examination of Measures to Prevent Passing-Related Accidents
35 on Two Lane Highways]. *Gesamtverband der Deutschen Versicherer, Forschungsbericht,*
36 *No.24* [German Insurance Association, German Insurance Accident Research], Berlin 2014.
- 37 4. Clarke, D. D., P. J. Ward and J. Jones. Overtaking Road-Accidents: Differences in Maneuver
38 as a Function of Driver Age. In *Accident Analysis & Prevention*, Volume 30, Issue 4, Great
39 Britain, 1998, pp. 455-467.
- 40 5. Persaud, B.N., R.A. Retting, and C.A. Lyon. Crash reduction following installation of
41 centerline rumble strips on rural two-lane roads. *Accident Analysis & Prevention*, 2004
- 42 6. Transportation Research Board (TRB), National Cooperative Highway Research Program
43 (NCHRP), NCHRP Report 605, *Passing Sight Distance Criteria*, Washington, DC., 2008.
- 44 7. Belz, N. Using Field and Simulation Data to Assess Passing Zone Behavior on Rural Two
45 Lane Highways. *98th Annual Meeting of the Transportation Research Board*, Washington, DC.,
46 2019.

- 1 8. Vettters, A., Thomas Jaehrig. Verification of the Existing Model for Passing Sight Distance on
2 Single Two-Lane Rural Carriageways, *6th IEEE International Conference on Cognitive*
3 *Infocommunications*. Győr, Hungary, 2015.
- 4 9. Carlson, P., J. Miles, and P. Johnson. Daytime High-Speed Passing Maneuvers Observed on
5 Rural Two-Lane, Two-Way Highway: Findings and Implications. *Transportation Research*
6 *Record*, Vol.1961, No. 1, Jan. 2006, pp. 9–15.
- 7 10. Llorca, C., A. Moreno, A. García, A. M. Pérez-Zuriaga and F. J. Camacho Torregrosa. Multiple
8 Passing Maneuvers: New Design and Marking Criteria to Improve Safety. *Road Safety and*
9 *Simulation International Conference, RSS2013*. Rome, Italy, 2013.
- 10 11. Polus, A., M. Livneh, and B. Frischer. Evaluation of the Passing Process on Two-Lane Rural
11 Highways. *Transportation Research Record: Journal of the Transportation Research Board*,
12 Vol.1701, 2000, pp. 53–60.
- 13 12. Llorca, C., and A. García. Evaluation of Passing Process on Two-Lane Rural Highways in
14 Spain with New Methodology Based on Video Data. *Transportation Research Record: Journal*
15 *of the Transportation Research Board*, Vol.2262, No. 1, Dec. 2011, pp. 42–51.
- 16 13. Harwood, D. W., D. K. Gilmore, and K. R. Richard. Passing Sight Distance Criteria for
17 Roadway Design and Marking. *Transportation Research Record: Journal of the Transportation*
18 *Research Board*, Vol.2195, 2010, pp. 36–46.
- 19 14. Llorca, C., and H. Farah. Passing Behavior on Two-Lane Roads in Real and Simulated
20 Environments. *Transportation Research Record: Journal of the Transportation Research*
21 *Board*, Vol.2556, No. 1, Jan. 2016, pp. 29–38.
- 22 15. Farah, H. Age and Gender Differences in Overtaking on Two-Lane Rural Highways.
23 *90thAnnual Meeting of the Transportation Research Board*, Washington, DC., 2011.
- 24 16. Younsi, K., J. Floris, B. Rajaonah, P. Simon, P. Loslever, and J.-C. Popieul. Study of Driver's
25 Behavior During Overtaking Situations. *Advances in Transportation Studies: An International*
26 *Journal*, Vol. 25, No. A 25, 2011, pp. 29–38.
- 27 17. American Association of State Highway and Transportation Officials (AASHTO). *A Policy*
28 *on Geometric Design of Highways and Streets*, Fifth Edition. Washington, DC., 2018.
- 29 18. Ed.German Road and Transportation Research Association, Committee, Geometric Design
30 Standards. Guidelines for the Design of Rural Roads, (RAL), Germany, 2012.
- 31 19. Harwood, D., D. Gilmore, and K. Richard. Passing Sight Distance Criteria for Roadway
32 Design and Marking. *Transportation Research Record: Journal of the Transportation*
33 *Research Board*, Vol. 2195, 2010, pp. 36–46.
- 34 20. Forbes, G. J. Origin of minimum passing sight distances for no-passing zones. *ITE Journal*
35 *(Institute of Transportation Engineers)*, Vol. 60, No. 12, 1990, pp. 20–24.
- 36 21. Pérez-Zuriaga, A.M, F. J. Camacho Torregrosa, A. García, C. Llorca, and A. Moreno.
37 Analyzing Speeding Behavior in Two-Lane Rural Roads. *Road Safety and Simulation*
38 *International Conference, RSS2013*.Rome, Italy, 2013.
- 39 22. Society of Automotive Engineers International. Taxonomy and Definitions for Terms Related
40 to Driving Automation Systems for On-Road Motor Vehicles. SAE International's On-Road
41 Automated Driving (ORAD) committee, United States.
42 https://saemobilus.sae.org/content/J3016_201609. Accessed Jun. 30, 2019
- 43 23. Garcia, A., D. Llopis Castello and F. J. Camacho Torregrosa. Influence of the Design of Crest
44 Vertical Curves on Automated Driving Experience. *98thAnnual Meeting of the Transportation*
45 *Research Board*, Washington, DC., 2019.

- 1 24. Mavromatis, S., E. Papadimitriou, G. Yannis and B. Psarianos. Vehicle Skidding Assessment
2 through Maximum Attainable Constant Speed Investigation. *Journal of Transportation*
3 *Engineering, American Society of Civil Engineers Part A: Systems*, Vol.143, Issue 9, ISSN
4 2473-2907, 2017.
- 5 25. Mavromatis, S. A. Laiou, G. Yannis. Safety Assessment of Control Design Parameters through
6 Vehicle Dynamics Model. *Accident Analysis and Prevention*. AAP491, Vol.125, 2019,
7 pp.344-351.
- 8 26. Mavromatis, S., A. Laiou, G. Yannis, B. Psarianos, Acceleration Impact Investigation for
9 Control Road Geometry Parameters. *97thAnnual Meeting of the Transportation Research*
10 *Board*, Washington, DC., 2018.
- 11 27. Gillespie T.D. Fundamentals of Vehicle Dynamics. *Society of Mining Metallurgy and*
12 *Exploration Inc.*1992.
- 13 28. Dixon J.C., Tires, Suspension and Handling. Second Edition. *Society of Automotive Engineers,*
14 *Inc Warrendale, Pa., United Kingdom* 1996.
- 15 29. Heisler H. Advanced Vehicle Technology. *Edward Arnold. A Division of Hobber & Stoughton,*
16 *Germany* 1993.
- 17 30. Mavromatis, S., and B. Psarianos. Analytical Model to Determine the Influence of Horizontal
18 Alignment of Two-Axle Heavy Vehicles on Upgrades. *Journal of Transportation*
19 *Engineering*, 129(6), 2003, pp. 583-589.
- 20 31. Mavromatis S, B.Psarianos, M., D'Apuzzo and V. Nicolosi. Design Speed Ranges to
21 Accommodate a Safe Highway Geometric Design for Heavy Vehicles. *Transportation*
22 *Research Board. 2nd International Symposium on Highway Geometric Design*, Mainz
23 *Germany* 14th-17th June 2000, pp.339-351.
- 24 32. Harwood, D. W. and J. M. Mason. Horizontal Curve Design for Passenger Cars and Trucks.
25 *Transportation Research Record 1445*, Transportation Research Board, Washington, DC.,
26 1994, pp. 22-33.
- 27 33. Edwards, C. H. Jr & Penney, D. E. Differential Equations and Boundary Value Problems:
28 Computing and Modeling, Prentice-Hall, New Jersey, 1996.
- 29 34. Vericom Computers. Vericom VC4000DAQ. Performance and Braking Test Computer,
30 Rev.1.10. Vericom Computers Inc., 2010, Rogers, MN USA.