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Two-Lane Highways Crest Curve Design. The Case Study of Italian Guidelines

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Abstract: The main purpose of the research is to evaluate the crest vertical curves radii R_v, not considering a conventional value of the opposing vehicle height h_2, but the average vehicle heights $h_{2(m)}$ and the value of the 15th percentile of the height distribution $h_{2(15)}$ of the passenger car population. The study only considered car models with more than 20,000 registered vehicles in Italy. One hundred and fifteen car models belonging to different brands were taken into consideration, for a total of over 9 million vehicles. For the statistical sample analyzed, the following vehicle heights were estimated: $h_{2(m)}$ = 1.48 m and $h_{2(15)}$ = 1.39 m. The deviations between the crest radii calculated with the Italian standard (h_2 = 1.10 m), and those obtained for $h_{2(m)}$ = 1.48 m and $h_{2(15)}$ = 1.39 m are up to 12%. The differences ΔH_v between the values of the visible vehicle body height $H_v = H_v(t)$ calculated using, respectively, $h_{2(15)}$ = 1.39 m and $h_{2(m)}$ = 1.48 m are modest. The value $h_{2(m)}$ = 1.48 m could be adopted in order to reduce the highways construction costs. In fact, the research shows that the value h_2 = 1.10 m is too conservative and leads to oversizing of the crest vertical curves. Therefore, it would be necessary to make an appropriate choice of h_2 value in order to take into account the current heights of passenger cars.

Keywords: two-lane highways; crest vertical curves; highways design; passing sight distance (PSD)

1. Introduction

In highway design, vertical curves have to be used to transition grade changes. Vertical curves should be chosen considering many relevant issues such as driver safety, comfort, alignment aesthetics, and drainage purposes [1–4]. Vertical curves are of two classes: convex vertical curves, known as crest curves, and concave vertical curves, known as sag curves [5,6]. Parabolic or circular curves are the common choices for vertical curves both in highway engineering [1,5,6] and in railway engineering [7,8]. Generally, parabolic curves are preferred, because they provide a constant rate of curvature change [6,9].

The main purpose of a crest curve's design is to calculate the minimum vertical curve radius ($R_{v,min}$) that complies the required sight distance (stopping sight distance SSD or passing sight distance PSD), according to total grade change Δi, design speed v, and drivers' comfort. As it is well known, too short a vertical curve radius may lead to insufficient sight distance.

Safe operation on crest vertical curves mainly depends on ample sight distance. Minimum stopping sight distance SSD should be ensured in all cases [6,9]. Table 1 shows the minimum radii of crest vertical curves as a function of design speed in various countries [6]. Wherever economically and technically feasible, passing sight distance PSD should be provided on two-lane highways [6,9].

In this article, the relationship between crest vertical curve radius R_v, passing sight distance PSD, driver eye height h_1, object (i.e., opposing vehicle) height h_2, and the characteristics of vehicle was obtained, considering for h_2 not a conventional value (i.e., h_2 = 1.10 m in the case of the Italian guidelines [10,11]) but the real vehicle heights. This is because, in recent decades, there has been a generalized significant increase in the vehicles' height. For example, the roof top height of modern sport utility vehicles (SUVs) is often more than 1.70 m. Therefore, in order to evaluate a reasonable value for h_2 a statistical sampling of the height of vehicles circulating in Italy was carried out. In particular, the average vehicle heights $h_{2(m)}$ and the value of the 15th percentile of the height distribution $h_{2(15)}$ have been calculated.

A comparative analysis between the vertical convex curves radii recommended in the Italian Guidelines for the Design of Road Infrastructures (h_2 = 1.10 m) [10] and the homologous values calculated with the analytical relationships proposed in this research (based on $h_{2(m)}$ and $h_{2(15)}$ parameters) was developed.

The results show that the h_2 value prescribed by the Italian guidelines [10,11] (h_2 = 1.10 m) is excessively precautionary, since it results in $h_{2(m)}$ = 1.48 m and $h_{2(15)}$ = 1.39 m, respectively. It follows the oversizing of the radius of vertical convex curves and their length, with consequent greater highways construction costs.

Table 1. Minimum radii of crest vertical curves as a function of design speed in various countries (source [6]).

	Design Speed [km/h]										
	40	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**
	Minimum Radius of Crest Vertical Curve [m]										
Austria	1500	2000	3000	4000	7500	-	12,500	-	20,000	-	35,000
Belgium	-	-	1600	-	-	7500	-	-	7824	-	-
Denmark	-	-	-	-	3500	-	6000	-	15,000	-	-
Germany											
1984	-	-	3750	3500	5000	7000	10,000	-	20,000	-	-
1995	-	1400	2400	3150	4400	5700	8300	-	16,000	-	-
New Research	-	-	800	1500	2700	4700	7600	-	17,500	-	-
France	700	-	1500	-	3000	-	6000	-	12,000	-	18,000
Italy	500	-	1000	-	3000	-	7000	-	14,000	-	-
The Netherlands	-	-	-	-	1800	-	4100	-	12,400	-	-
Spain	-	-	-	-	3500	-	6000	-	12,000		
Sweden	-	1100	-	3500	-	7000	-	10,000	-	-	-
Sweden *	-	600 *	-	1800 *		1800 *	-	-	-	-	-
Switzerland	620	1500	2100	3000	4200	-	10,500	-	18,000	-	31,000
United Kingdom	-	1100	1900	3300	5900	-	10,500	-	18,000	-	-
Canada	400	700	1500	2200	3500	5500	7000	8500	10,500	12,000	-
United States	500	1000	1800	3100	4900	7100	10,500	15,100	20,200	-	-
South Africa	600	-	2000	-	5000	-	10,000	-	20,000	-	-
Australia	-	540	920	1570	2400	4200	6300	9500	13,500	19,500	-
Japan	-	800	1400	-	3000	-	6500	-	11,000	-	-
Greece	-	1500	2500	3200	4300	5700	7400	11,000	15,000	20,000	-

Note: * Exceptional value.

2. The Overtaking Maneuver and the Passing Sight Distance (PSD)

The overtaking maneuver is a key issue for two-lane highways, because it requires occupying the opposing lane, which represents a serious safety concern [6,9,12,13].

Accidents occurred due to overtaking maneuvers represent around 38% of the total accidents on Italian two-lane highways [14]. Accident severity associated to overtaking maneuvers is usually higher than in other maneuver types [12,13].

The overtaking maneuver's frequency depends on various factors, including traffic volumes, users' motivation, and their psychophysical state and highway alignment (vertical and horizontal) [15]. The traffic flow variable that considerably influences the propensity to do an overtake maneuver is the vehicular density k. In steady-state traffic condition [16–18], the density k can be estimated by knowing the flow rate q and the mean space speed v_s, with the well-known fundamental relations of traffic flow: $k = q/v_s$.

As q increases for a given vehicle, the probability of encountering slow vehicles increases [19]. In other words, users have high probability to encounter slower vehicles and often are forced to queue up first and then overtake where the available sight distance D is greater than the passing sight distance PSD [19]. Consequently, the performance analyses of two-lane highways—whose objective is to determine the level of service (LOS) for an existing or proposed facility—include a specific evaluation of the percent time-spent-following [20].

Then, a PSD adequate for users to pass slow vehicles should be provided at frequent intervals on two-lane highways. In order to guarantee acceptable LOS, several highway design guidelines require a minimum percentage of passing zones in each direction of travel (e.g., 20% in Italy [10]).

To ensure suitable safety conditions, overtaking is only allowed in the zones where available sight distance is higher than the required overtaking passing sight distance PSD [12,21]. PSD is defined as the distance required to complete an overtaking maneuver when an opposing vehicle is approaching in the opposing lane.

The PSD can be estimated by means of several overtaking models. In the Italian model [10] (Figure 1), the speed v of overtaking vehicle (A) is assumed to be uniform during the right and left lanes occupation time. The speed of the overtaken vehicle B is v − Δv. Instead, the speed of the opposing vehicle C, in the opposing lane, is v.

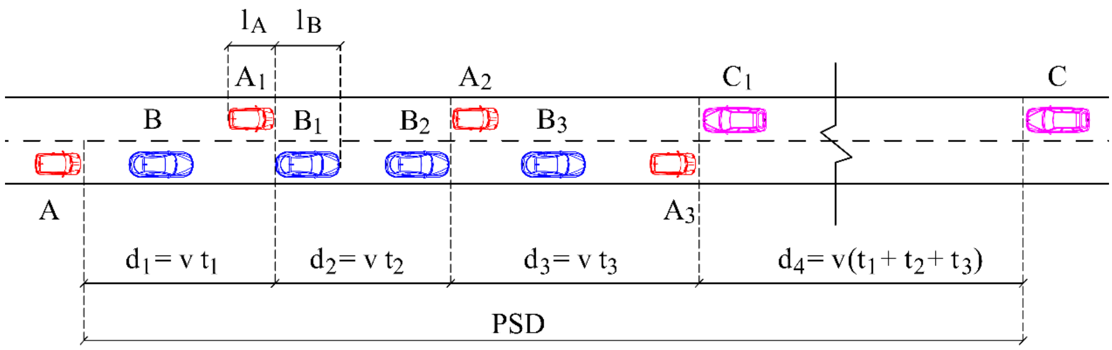

Figure 1. Overtaking maneuver phases (Italian model [10,22]).

The minimum passing sight distance PSD is the sum of four subintervals [22]: $d_1 = v \cdot t_1$; $d_2 = v \cdot t_2$; $d_3 = v \cdot t_3$; $d_4 = v \cdot (t_1 + t_2 + t_3)$, in which:

- v: design speed of the highway segment under analysis expressed in m/s;
- $t_1 = 4$ s: time for lane change (from the right lane to the opposing lane);
- $t_2 = 2$ s: overtaking time (at the end of this time interval the rear bumper of vehicle A and the front bumper of vehicle B are at the same road section);
- $t_3 = 4$ s: time for lane change (from the opposing lane to the right lane).

Therefore, the minimum passing sight distance PSD is:

$$PSD = 2v\,(t_1 + t_2 + t_3) = 2v\left(t_1 + \frac{2l_m}{\Delta v} + t_3\right) \quad (1)$$

where:

- $l_m = (l_A + l_B)/2$;
- l_A length of the vehicle A;
- l_B length of the vehicle B.

Since $\frac{l_m}{\Delta v} \cong 1$ s, it results in:

$$PSD = 20v = 5.5\,V\,[m] \quad (2)$$

in which V is the design speed expressed in km/h.

Figure 2 illustrates a comparison of minimum PSD values obtained with the several widespread models of Table 2, including the Italian model, in function of the highway design speed V.

Table 2. Passing sight distance (PSD) models.

Model Name or Country	Relationships
Italy [10]	$PSD = 5.5\ V$
Switzerland [23]	$PSD = 6.7\ V$
France [24]	$PSD = 550\ [m]$
Lieberman model [25]	$PSD = d_5 + PSD_c$ $d_5 = G_1^N + 1.47t_5 + \Delta_c$ $PSD_c = 1.47(2V_1 + m)t_6 + d_3$ $t_6 = 0.68\left[\left(\frac{G_1+\Delta_c}{m}\right)\right] + \left(\frac{1.47m}{2a}\right)$ $\Delta_c = G_1 - 1.47mt_6$ $a = a_{max}\left[1 - \frac{V_1+\frac{m}{2}}{V_{max}}\right]$
Glennon model [26]	$PSD = 2V_d\left(2.93 + \frac{L_p-\Delta_c}{m}\right)$ $\Delta_c = L_p + 1.47m\left\{\frac{(2.93+L_i+L_p)}{1.47(2V_d - m)} - \left[\frac{5.87V_d(2.93m+L_i+L_p)}{1.47d_a(2V_d-m)}\right]^{\frac{1}{2}}\right\}$
Hassna et al. Model [27]	$PSD_c = 2.93V_d(t_6 + h)$ $t_6 = p_a + t_a - \frac{d_a t_a}{5.88V_d}(t_a + 2h)$ $t_a = -h + \sqrt{\frac{h^2+5.88V_d[L_p+L_i+1.4h(2V_d-m)]}{1.47d_a(2V_d-m)}}$ $\Delta_c = L_p + 1.47(V_d - m)h - 1.47mt_6$ $PSD_c = 2.93V_d\left(t_6^* + h\right)$ $t_6^* = \frac{1.47(V_d-m)h+L_p}{1.47m}$ $PSD_c = 2.93V_d(t_6 + h)\ \Delta_c \le 0$ $PSD_c = 2.93V_d\left(t_6^* + h\right)\ \Delta_c \ge 0$
Van Valkenburg and Michael model [28]	PSD = 230 m for V = 50 km/h PSD = 365 m for V = 70 km/h PSD = 575 m for V = 110 km/h
Rilett et al. model [29]	$PSD_{complete} = 1.47V_{crit}t_5 + \frac{1.47at_3^2}{2} + 1.47V_d t_6 d_3 + 1.47V_0(t_5 + t_6)$ $PSD_{short} = 1.47V_{crit}p_a + 1.47V_{crit}t_8 - \frac{1.47dt_5^2}{2} + 1.47V_{min}t_9 + d_3 + 1.47V_0\left(p_a + t_8 + t_9\right)$
American Association of State Highway and Transportation Officials-AASHTO Green Book [30]	$PSD = d_1 + d_2 + d_3 + d_4$ $d_1 = \frac{t_1}{3.6}\left(V - m - \frac{at_1}{2}\right)$ $d_2 = \frac{1}{3.6}Vt_2$ $30\ m \le d_3 \le 90\ m$ $d_4 = 2/3\ d_2$

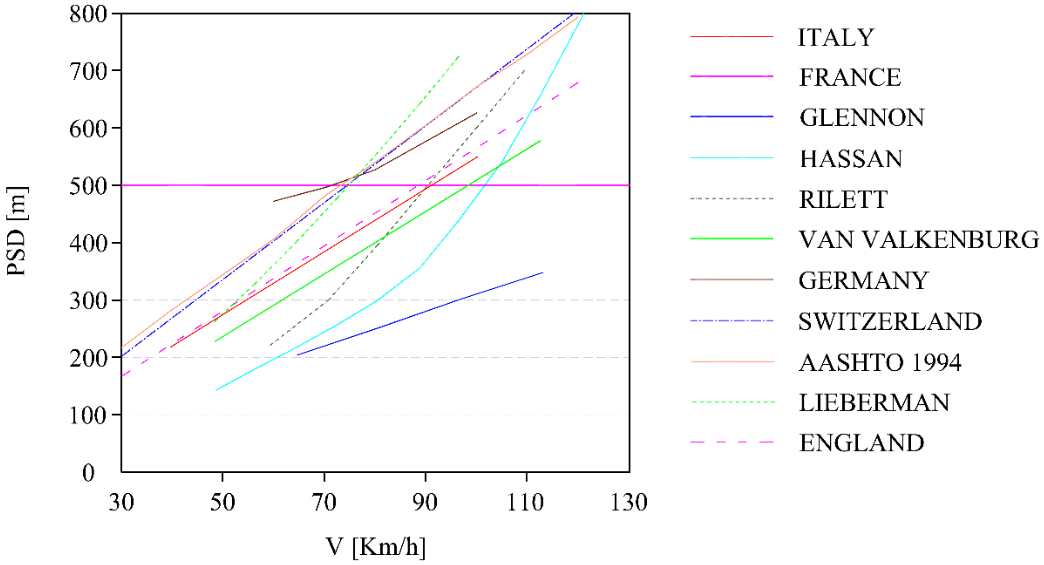

Figure 2. Passing sight distance (PSD) models comparison.

3. Analytical Derivation of Crest Curve Minimum Radius

The minimum radius of crest curves based on passing sight distance (PSD) criteria generally is satisfactory from the standpoint of safety, comfort, and appearance [15,22]. In this section, the detailed derivation process for the analytical relationship between passing sight distance (PSD), driver eye height h_1, object (i.e., opposing vehicle) height h_2, and the necessary parabolic vertical crest curve radius R_v is presented.

Let the left-hand side road grade be i_1, and right-hand side road grade i_2, the total grade change $\Delta i = i_2 - i_1 < 0$ (assuming $i_2 < i_1$), and L the crest vertical curve length. The origin of the coordinates is selected at point O (beginning of the vertical curve) (Figure 3). If the vertical curve follows a parabolic shape, the curve equation is:

$$y = ax^2 + bx \tag{3}$$

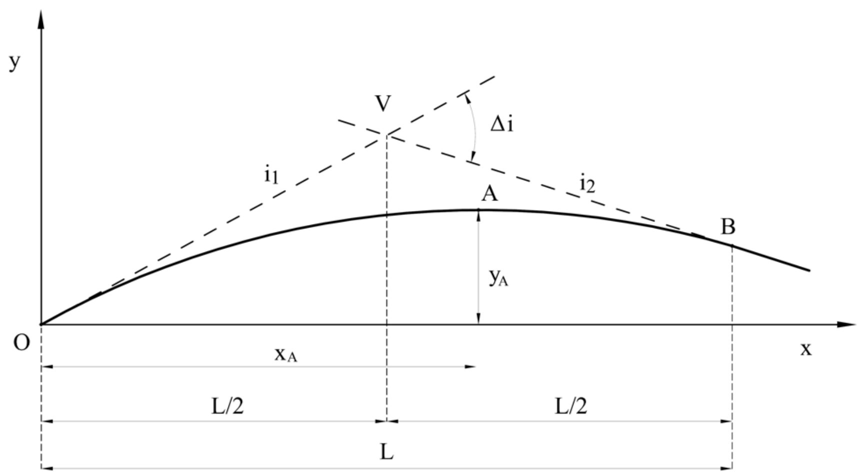

Figure 3. Parameters considered in determining the crest vertical curve radius.

The coefficients a and b can be obtained by the following boundary conditions:

$$\left(\frac{dy}{dx}\right)_{x=0} = b \quad \text{therefore} \quad b = i_1 \tag{4}$$

$$\frac{d^2y}{dx^2} = 2a \quad \text{therefore} \quad a = \frac{\Delta i}{2L} \tag{5}$$

The vertical curve equation $y = ax^2 + bx$ can be rewritten as Equation (6)

$$y = \frac{\Delta i}{2L}x^2 + i_1 x \tag{6}$$

the coordinates in the summit of the parabola (point A of Figure 3) are:

$$x_A = -\frac{i_1}{\Delta i}L \tag{7}$$

$$y_A = -\frac{i_1^2}{2\Delta i}L \tag{8}$$

the relationship of the curvature is:

$$\frac{1}{R} = \frac{\frac{\Delta i}{L}}{\left[1 + \left(\frac{\Delta i}{L}x + i_1\right)^2\right]^{\frac{3}{2}}} \tag{9}$$

Equation (9) allows to calculate the radius of the osculating circle in the points O, A, and B:

$$R_o = \frac{\left[1 + i_1^2\right]^{\frac{3}{2}}}{\Delta i}L \tag{10}$$

$$R_B = \frac{\left[1 + (i_1 + \Delta i)^2\right]^{\frac{3}{2}}}{\Delta i}L \tag{11}$$

$$R_A = \frac{L}{\Delta i} \tag{12}$$

The minimum radius of curvature R_v is located at point A, therefore we can assume $R_v = R_A$. Let D = PSD (cfr. Figure 4). The relationship between the minimum radius of curvature R_v, the passing sight distance D, the driver eye height h_1, object (i.e., opposing vehicle) height h_2, and the total grade change Δi can be derived using the geometric schemes, as depicted in Figure 4. More specifically, Figure 4 illustrates the influence of vertical curvature on visibility. Two conditions must be considered [1,9,22,31]:

a. Passing sight distance is shorter than vertical curve length (D < L);
b. Passing sight distance is longer than vertical curve length (D > L).

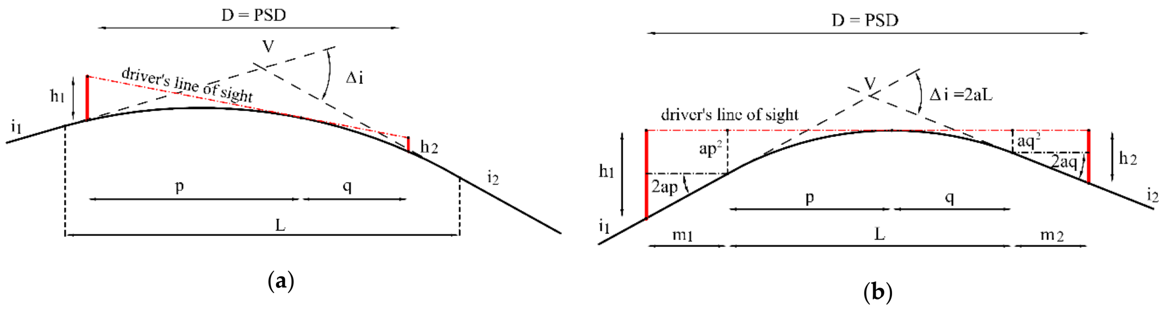

Figure 4. Crest curve radius derivation (case (**a**): D < L; case (**b**): D > L).

3.1. Case in Which D < L

Consider the case in which the passing sight distance is shorter than the vertical curve length (D = PSD < L). Using the geometric parameters in Figure 4, it results in [22]:

$$h_1 = ap^2 \tag{13}$$

$$h_2 = aq^2 \tag{14}$$

$$D = p + q = \frac{1}{\sqrt{a}} \cdot \left(\sqrt{h_1} + \sqrt{h_2} \right) \tag{15}$$

$$L = \frac{\Delta i \cdot D^2}{2 \cdot \left(h_1 + h_2 + 2\sqrt{h_1 \cdot h_2} \right)} \tag{16}$$

$$R_V = R_A = \frac{L}{\Delta i} = \frac{D^2}{2 \cdot \left(h_1 + h_2 + 2\sqrt{h_1 \cdot h_2} \right)} \tag{17}$$

According to Equation (17), the minimum radius of curvature R_v (point A of Figure 3) is not a function of the total grade change Δi.

3.2. Case in Which D > L

Consider the case in which the passing sight distance is longer than the vertical curve length (D = PSD > L). Using the geometric parameters in Figure 4, it results in [22]:

$$h_1 = a \cdot p^2 + 2 \cdot a \cdot p \cdot m_1 \tag{18}$$

$$h_2 = a \cdot q^2 + 2 \cdot a \cdot q \cdot m_2 \tag{19}$$

$$m_1 = \frac{h_1}{2 \cdot a \cdot p} - \frac{p}{2} \tag{20}$$

$$m_2 = \frac{h_2}{2 \cdot a \cdot q} - \frac{q}{2} \tag{21}$$

$$D = m_1 + L + m_2 = \frac{h_1}{2 \cdot a \cdot p} + \frac{h_2}{2 \cdot a \cdot (L - p)} + \frac{L}{2} \tag{22}$$

The minimum value of the sight distance can be obtained deriving the Equation (22) and by the following condition:

$$\frac{dD}{dp} = \frac{-h_1}{2 \cdot a \cdot p^2} + \frac{h_2}{2 \cdot a \cdot (L - p)^2} = 0 \tag{23}$$

then

$$p = \frac{L}{1 + \sqrt{\frac{h_2}{h_1}}} \tag{24}$$

$$q = L - p = p \cdot \sqrt{\frac{h_2}{h_1}} \tag{25}$$

plug Equations (24) and (25) into Equation (22), after minor rearrangement, it results in:

$$D = \frac{L}{2} + \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \tag{26}$$

$$L = 2 \cdot \left(D - \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \right) \tag{27}$$

$$R_V = R_A = \frac{2}{\Delta i}\cdot\left(D - \frac{h_1 + h_2 + 2\cdot\sqrt{h_1\cdot h_2}}{\Delta i}\right) \quad (28)$$

According to Equation (28), the minimum radius of curvature R_v (point A of Figure 3) is a function of the total grade change Δi.

4. Passing Sight Distance, Opposing Vehicle Height h_2, and Eye Height h_1

An object (i.e., opposing vehicle) height of h_2 = 1.10 m is adopted by the Italian Guidelines for the Design of Road Infrastructures [10] for the calculation of passing sight distance PSD. Such value appears not to be in compliance with the average height of the current passenger car population. In fact, over the past few decades, sales of sport utility vehicles (SUVs) have increased. At the same time, even utility cars have undergone increases in overall size and, in particular, in height.

For this reason, a specific analysis was carried out concerning the Italian passenger car population until 2006, coinciding with the year of publication of the latest Italian Guidelines for the Design of Road Intersections [11].

The research was carried out using the Italian car population data updated to 31 December 2006, registered by the Italian Automobile Club (ACI) and by the Public Vehicle Registration Office (PRA) [32]. On that date, the vehicles circulating in Italy were 35,297,282. The study only considered car models with more than 20,000 registered vehicles. Specifically, 115 vehicle models belonging to different brands were taken into consideration, for a total of over 9 million vehicles. For each of the 115 models considered, the overall height was deduced.

Table 3 shows the summary data. In the study, the average vehicle heights $h_{2(m)}$ and the value corresponding to the 15th percentile of the height distribution $h_{2(15)}$ were estimated, obtaining, respectively, the values $h_{2(m)}$ = 1.48 m and $h_{2(15)}$ = 1.39 m.

As shown in the histogram of Figure 5, the largest number of registered vehicles (4,151,428) falls in the height range 1.40–1.44 m, follow the intervals 1.45–1.49 m and 1.50–1.54 m, with 1,449,211 and 1,100,024 vehicles, respectively. The sum of the vehicles falling into these three classes is 6,700,663, namely the 73% of the number of passenger cars examined.

According to the Italian Guidelines for the Design of Road Infrastructures and Intersections [10,11], the obstacle that the driver must be able to see during the overtaking maneuver (i.e., opposing vehicle) has a height h_2 = 1.10 m. Evidently, this is a very conservative value compared to the inferred values $h_{2(m)}$ = 1.48 m and $h_{2(15)}$ = 1.39 m. The remarkable differences between the height of the obstacle provided by the Italian guideline (h_2) and those derived from the real passenger car population ($h_{2(m)}$ and $h_{2(15)}$) lead to significant differences in the values of the radii of the crest curve (R_v). Instead, the driver's eye height h_1 = 1.10 m is congruent with the values adopted internationally (Table 4) [33].

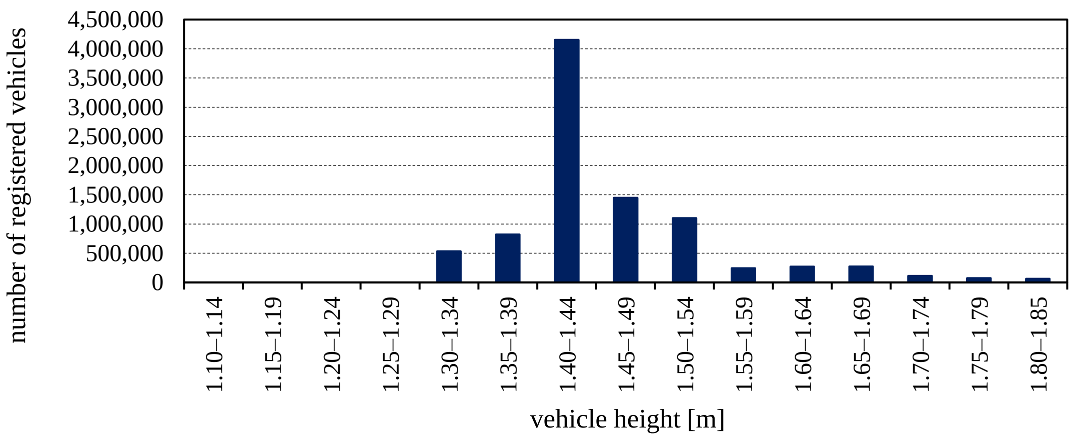

Figure 5. Absolute frequency distribution of passenger cars heights.

Table 3. Top 20 car models registered in Italy listed by number of vehicles sold.

N.	Brand	Model		Number of Vehicles Registered (Year 2006)	Overall Height h [mm]
1	Fiat	Seicento	1.1I	480,518	1430
2	Fiat	Panda	900 IE	466,607	1440
3	Fiat	Uno	45 3P	448,715	1430
4	Lancia	Y	1.2I	439,421	1440
5	Fiat	Punto	55 3P	438,184	1480
6	Fiat	500	L	381,766	1330
7	ford	Ka	1.3	232,805	1370
8	Renault	Clio	1.1I 3P	223,814	1420
9	Renault	Twingo	1.2	222,087	1420
10	Fiat	Panda	1.2	222,035	1540
11	Opel	Corsa	1.0I 12V 3P	219,870	1440
12	Autobianchi	Y10	Fire	175,018	1430
13	Ford	Focus	1.8 TDDI 5P	167,753	1500
14	Toyota	Yaris	1.0I 16V 3P	157,158	1530
15	Volkswagen	Golf	1.9 TDI Variant	126,521	1490
16	Peugeot	206	1.4	120,518	1430
17	Nissan	Micra	1.0 CAT	116,472	1540
18	Alfa Romeo	147	1.9 JTD	113,463	1440
19	Fiat	Tipo	1.4 5P	109,294	1450
20	Renault	Megane	1.9 DCI Scenic	107,323	1620
...	...	...	...	...	...
115	Honda	Jazz	1.2I DSI	20,314	1530
	-	-	TOTAL	9,154,262	...

Table 4. Driver's eye height h_1 adopted in some countries.

Country	Driver Eye Height [m]	
	Passenger Car	Truck
Australia	1.15	1.80
Austria	1.00	-
France	1.00	-
Germany	1.00	2.50
Greece	1.10	-
Japan	1.20	1.50
South Africa	1.05	1.80
Sweden	1.10	-
Switzerland	1.00	2.50
United Kingdom	1.05	-

Minimum Values of R_v

Figure 6 shows R_v values according to the Equations (17) and (28) obtained for h_1 = 1.10 m and $h_{2(15)}$ = 1.39 m. Similarly, Figure 7 shows R_v values according to the Equations (17) and (28) obtained for h_1 = 1.10 m and $h_{2(m)}$ = 1.48 m. In both cases, each curve $R_v(\Delta i)$ reaches a maximum value R_v * for $\Delta i = \Delta i$ *; instead, for $\Delta i > \Delta i$ *, it results in $R_v = R_v$ *. As can be observed from Figure 8, the differences ΔR_v between R_v values calculated in the two scenarios ($h_{2(15)}$ = 1.39 m and $h_{2(m)}$ = 1.48 m) increase with increasing PSD. Finally, Figures 9 and 10 show the differences (ΔR_v) between the vertical radii calculated with the Italian model (h_2 = 1.10 m) and the values obtained, respectively, for $h_{2(m)}$ = 1.48 m and $h_{2(15)}$ = 1.39 m. It should be noted that the deviations are up to 12%.

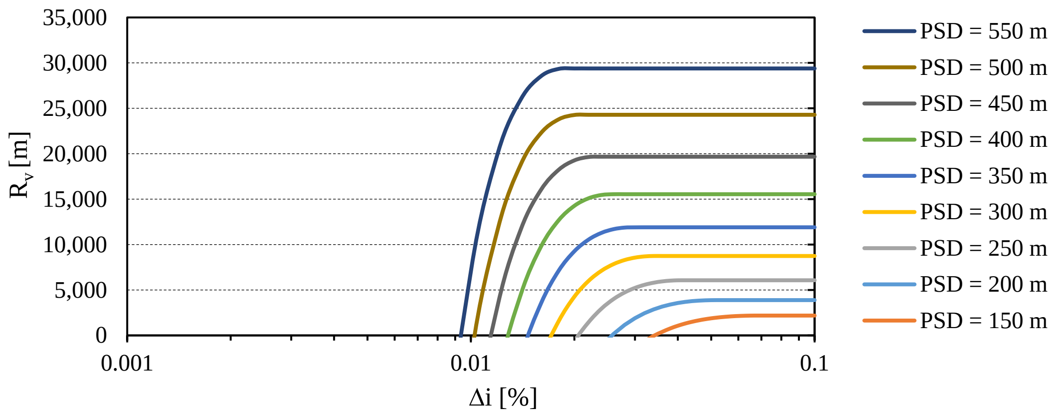

Figure 6. R_v values (h_1 = 1.10 m and $h_{2(15)}$ = 1.39 m).

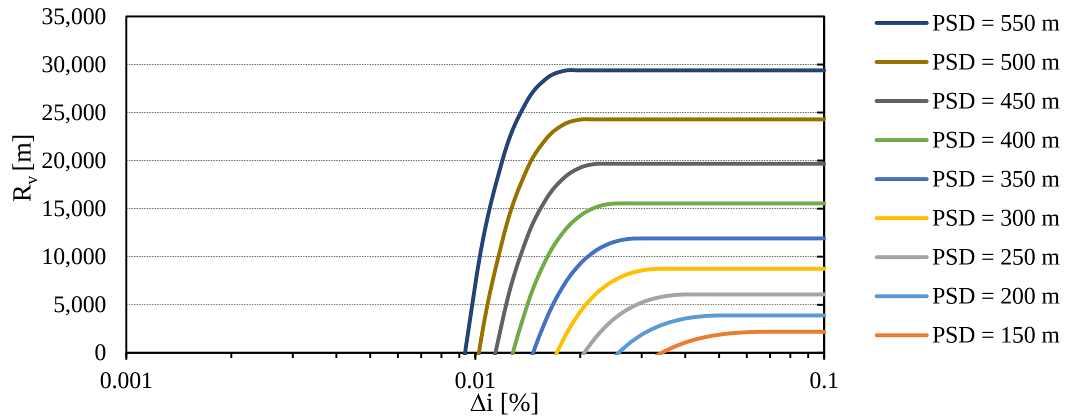

Figure 7. R_v values (h_1 = 1.10 m and $h_{2(m)}$ = 1.48 m).

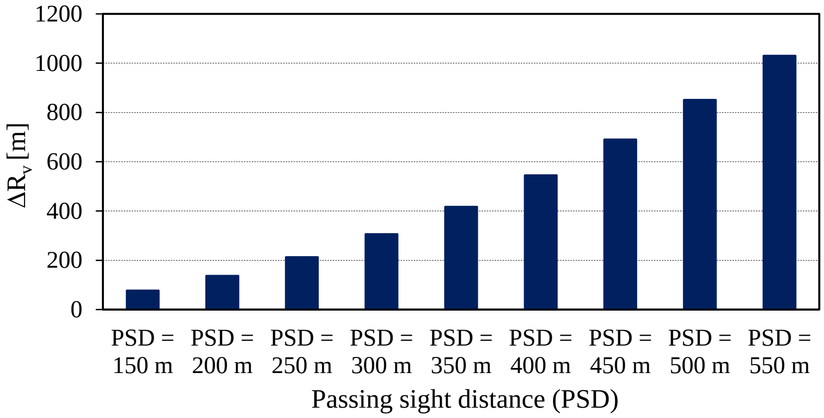

Figure 8. ΔR_v between R_v values calculated for $h_{2(15)}$ = 1.39 m and $h_{2(m)}$ = 1.48 m.

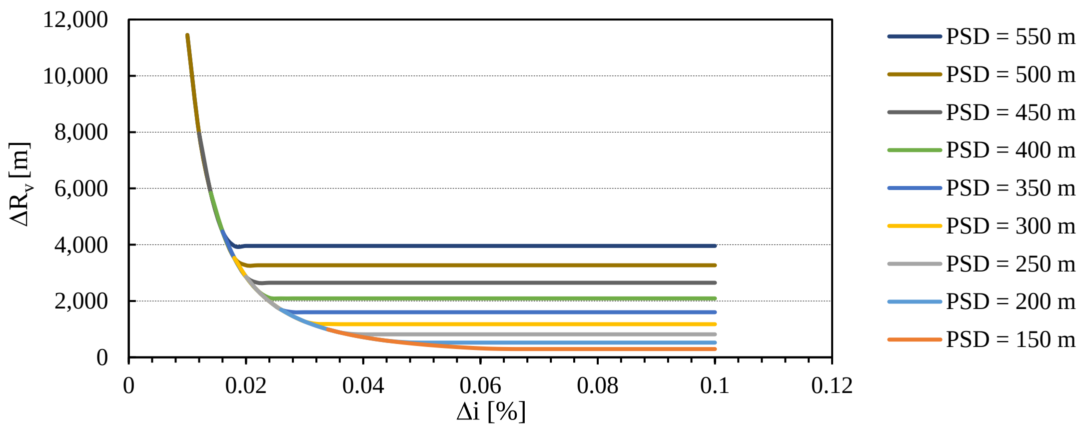

Figure 9. ΔR_v between R_v values calculated for h_2 = 1.10 m [10] and $h_{2(15)}$ = 1.39.

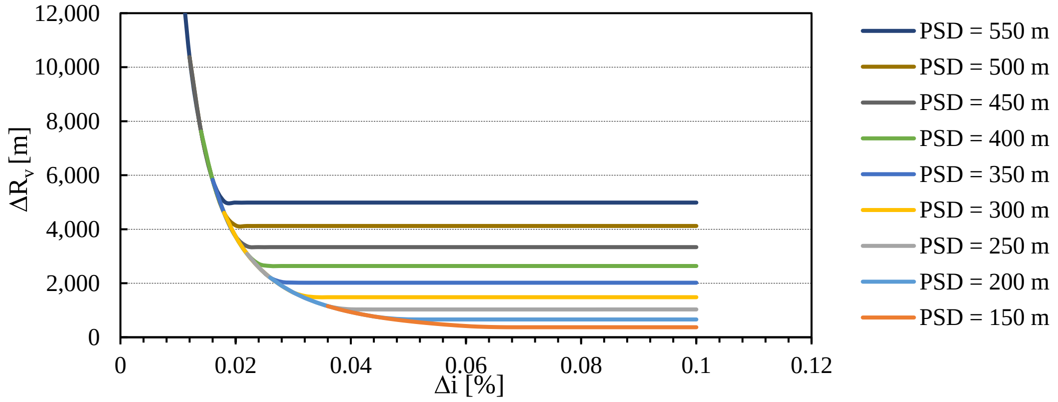

Figure 10. ΔR_v between R_v values calculated for h_2 = 1.10 m [10] and $h_{2(m)}$ = 1.48 m.

5. Visible Vehicle Body Height in Function of Time

In this section, the relationship between the design speed v, the time t of vehicles traveling along a crest curve in opposing lanes, and the visible vehicle body height H_v is deduced (Figure 11). H_v value increases as the vehicles approach each other.

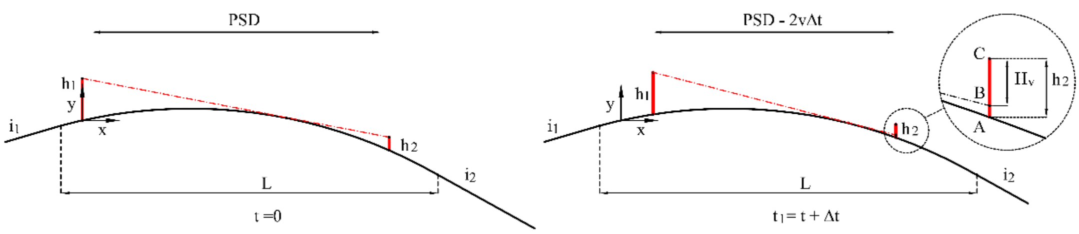

Figure 11. Visible vehicle body height H_v.

To obtain the function $H_v = H_v(t)$, consider Figure 11.

At the time instant t = 0, the driver's eye has coordinates (0; 1.10) and is able to see, at a distance D equal to PSD, the roof top of the vehicle traveling in the opposite direction. The driver's line of sight (cfr. Figure 4) is tangent to the parabola and intersects the moving obstacle (opposing vehicle) at a height h_2.

At time t = 0, the visible vehicle body height is $H_v = 0$. After a time interval Δt, the overtaking vehicle covers a highway segment $\Delta x = v \cdot \Delta t$ long, as did the vehicle traveling in the opposite direction. Then, the visible vehicle body height is $H_v > 0$.

Assuming once again that the vertical curve follows a parabolic shape, we can easily infer the function $H_v = H_v(t)$:

$$y_p = bx - ax^2 \tag{29}$$

in which:

$$b = i_1$$
$$a = \frac{\Delta i}{2L}$$

therefore:

$$y_p = i_1 x - \frac{\Delta_i}{2L} x^2 \tag{30}$$

the driver's line of sight equation is:

$$y_r = mx + n \tag{31}$$

Imposing the condition $y_p = y_r$, we get:

$$y_r = y_p \Rightarrow i_1 x - \frac{\Delta i}{2L} x^2 = mx + n \tag{32}$$

$$(i_1 - m)x - \frac{\Delta i}{2L} x^2 - n \Rightarrow \frac{\Delta i}{2L} x^2 - (i_1 - m)x + n = 0 \tag{33}$$

Since the driver's line of sight must be tangent to the crest curve, the following condition must be imposed:

$$\Delta = b^2 - 4ac \Rightarrow (i_1 - m)^2 - 4\frac{\Delta i}{2L} n = 0 \tag{34}$$

$$\left(i_1 - m^2\right) = \frac{4\Delta i}{2L} n \tag{35}$$

$$i_1 - m = \sqrt{\frac{4\Delta i}{2L} n} \Rightarrow m = i_1 - \sqrt{\frac{4\Delta i}{2L} n} \tag{36}$$

For the abscissa x, y_r is

$$y_r = AB + BC \tag{37}$$

$$y_r = \left(i_1 - \sqrt{\frac{4\Delta i}{2L} n}\right) x + n = \left(i_1 x - \frac{\Delta i}{2L} x^2\right) + h_1 \tag{38}$$

with

$$AB = \left(i_1 x - \frac{\Delta i}{2L} x^2\right) \tag{39}$$

$$BC = h_1 \tag{40}$$

$$x = v \cdot \Delta t \tag{41}$$

$$\left(i_1 - \sqrt{\frac{4\Delta i}{2L} n}\right) \cdot v \cdot \Delta t + n - i_1 \cdot v \cdot \Delta t + \frac{\Delta i}{2L} \cdot v^2 \cdot \Delta t^2 - h_1 = 0 \tag{42}$$

$$n - \sqrt{\frac{4\Delta i}{2L} n} \cdot (v \cdot \Delta t) + \frac{\Delta i}{2L} \cdot v^2 \cdot \Delta t^2 - h_1 = 0 \tag{43}$$

Then, we found n and y_r.

In conclusion, H_v (Figure 11) can be determined using the following Equation (44):

$$H_v = BC = AC - AB = h_2 - (y_r - y_p) \tag{44}$$

With Equation (44), the values of H_v were then calculated considering $h_{2(m)} = 1.48$ m and $h_{2(15)} = 1.39$ m, respectively. By way of example, in Figure 12, the visible vehicle body height H_v values are given in function of time t, for a design speed V = 100 km/h, road grade $i_1 = 1\%$, and total grade variation $\Delta i = 0.02\%$. Using Equation (2) for V = 100 km/m, we have PSD = 5.5 V = 550 m. By Equation (17), it results in:

- $R_v = 30{,}400$ m for $h_{2(15)} = 1.39$ m;
- $R_v = 29{,}500$ m for $h_{2(m)} = 1.48$ m.

Despite this significant difference in the values of the radius, it is immediate to note that the differences ΔH_v between the values of the visible vehicle body height $H_v = H_v(t)$ calculated using $h_{2(15)} = 1.39$ m and $h_{2(m)} = 1.48$ m, respectively, are modest for each instant of time t. As a matter of fact, ΔH_v reaches 4.0 cm at time instant t = 2 s. In light of these considerations, the value $h_{2(m)} = 1.48$ m could be adopted in the design phase of crest curves in order to reduce the highways construction costs and the correlated environmental impacts [34–40].

It is worth underlining that, for the sake of safety [41,42], it could be used a vehicle height of 1.38 m ($h_2 = 1.38$ m), which represents the average of vehicle heights in the current passenger car population ($h_{2(m)} = 1.48$), less an allowance of 100 mm, which represents a near-maximum value for the portion of the vehicle height that needs to be visible for another driver to recognize a vehicle as such [33,43]. Anyhow, the vehicle height $h_2 = 1.10$ m is too conservative compared to car population real values.

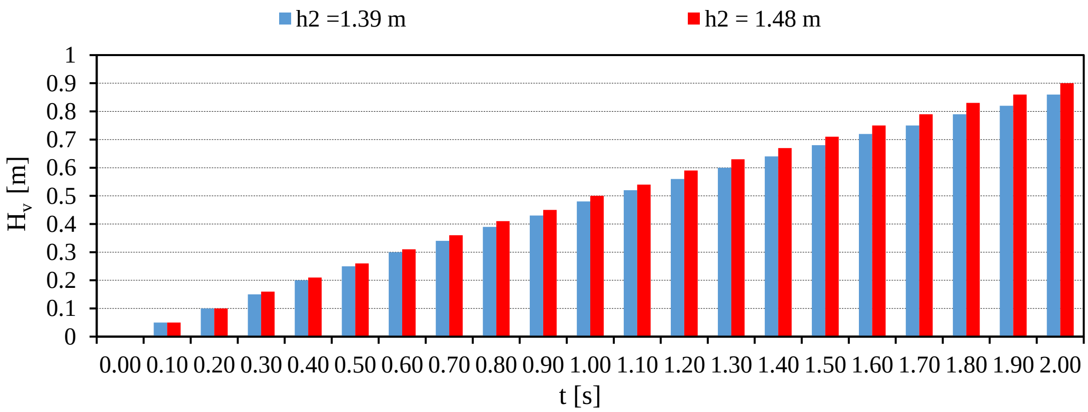

Figure 12. Visible vehicle body height H_v in function of time t (design speed V = 100 km/h).

6. Conclusions

The passing sight distance PSD can be evaluated with several overtaking models. These models give rise to dissimilar results due to the different values assigned to parameters, such as vehicles kinematic parameters (accelerations, speeds, etc.) and behavior parameters of the users involved in the overtaking maneuver. PSD affects both the safety and level of service (LOS) of two-lane highways. For this reason, PSD is of fundamental importance in highways design and traffic engineering.

In particular, safe operation on crest vertical curves depends on ample sight distance; therefore, the stopping sight distance (SSD) must always be ensured. With the aim to guarantee acceptable LOS, wherever technically feasible, passing sight distance PSD should also be provided on two-lane highways.

As it is well known, the crest vertical curve radius R_v is a function of passing sight distance (PSD), driver eye height h_1, object height (i.e., opposing vehicle) h_2, and total grade change Δi.

The Italian Guidelines for the Design of Road Infrastructures and Intersections prescribe $h_2 = 1.10$ m, which is too conservative a value in comparison to the average height of the vehicles $h_{2(m)}$ and the 15th percentile of the height distribution $h_{2(15)}$ of the car population in Italy. In fact, the research proved that $h_{2(m)} = 1.48$ m and $h_{2(15)} = 1.39$ m. Using these object height values, the crest curves radii R_v have been calculated, and they have next been compared with those prescribed by the Italian guidelines. Reductions up to 12% were found. Moreover, the relationship between the design speed V, the time t of vehicles traveling along a crest curve in opposing lanes, and the visible vehicle body height H_v has been deduced. It was thus possible to ascertain that, by adopting $h_{2(m)} = 1.48$ m and $h_{2(15)}$ = 1.39 m, the differences in the H_v values are very limited and never exceed 4 cm within 2 s starting from an initial instant corresponding to a reciprocal position among the vehicles equal to the PSD.

In conclusion, it is believed that the value h_2 = 1.10 m is too conservative and leads to oversizing of the vertical convex curves. From this point of view, it would be necessary to make an appropriate choice of h_2 value to take into account the current heights of passenger cars.

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Nomenclature

a	acceleration rate
d_i i = 1,2, ... , 6	subinterval of PSD (depending on the model in Table 2)
d	deceleration rate of passing vehicle abortion
D	available sight distance
Δ_c	vehicle critical position
G_1	distance between the rear bumper of the passing vehicle and the front bumper of the impeding vehicle at the end of a completed pass
h	headway
h_1	driver's eye height
h_2	opposing vehicle height
$h_{2(m)}$	average vehicle heights of the passenger car population in Italy
$h_{2(15)}$	15th percentile of the height distribution of the passenger car population in Italy
H_v	visible vehicle body height
i_1	left-hand side road grade
i_2	right-hand side road grade
Δi	total grade change
k	traffic density
L	crest vertical curve length
L_p	length of passing vehicle
L_i	length of impeding vehicle
m = Δv	difference in speed between passing and impeding vehicles
PSD	passing sight distance
q	traffic flow rate
R_v	crest vertical curves radius
SSD	stopping sight distance
t	time
v	design speed in m/s
V	design speed in km/h
v_s	mean space speed

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