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 $\Delta H_v$ 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 $\Delta i$, 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] | Minimum Radius of Crest Vertical Curve [m] |
|---------------------|------------------------------------------|
|                     | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 |
| 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 | - | - |
| Germany 1995        | - | 1400 | 2400 | 3150 | 4400 | 5700 | 8300 | - | 16,000 | - | - |
| New Research        | - | - | 800 | 1500 | 2700 | 4700 | 7600 | - | 17,500 | - | - |
| France              | 400 | 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 *            | - | 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.

![Overtaking maneuver phases](https://via.placeholder.com/150)

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

The minimum passing sight distance PSD is the sum of four subintervals [22]:

\[
d_1 = v \cdot t_1; \quad d_2 = v \cdot t_2; \quad d_3 = v \cdot t_3; \quad d_4 = v \cdot (t_1 + t_2 + t_3),
\]

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:

\[
\text{PSD} = 2v \left( t_1 + t_2 + t_3 \right) = 2v \left( t_3 + \frac{2l_m}{\Delta v} + t_3 \right)
\]

(1)

where:

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

Since \( \frac{l_m}{\Delta v} \approx 1 \) s, it results in:

\[
\text{PSD} = 20v = 5.5 \ V \ [m]
\]

(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]

$$
\text{PSD} = d_5 + \text{PSD}_c \\
\text{PSD}_c = 1.47(2V_1 + m)t_6 + d_3 \\
t_6 = 0.66\left(\frac{G_1 + \Delta_c}{m}\right) + \left(\frac{1.47m}{2a}\right) \\
\Delta_c = G_1 - 1.47mt_6 \\
a = a_{\text{max}}\left[1 - \frac{V_1 + \Delta_c}{V_{\text{max}}}\right]
$$

Glennon model [26]

$$
\Delta_c = L_p + 1.47m\left\{ \frac{(2.93t_6 + L_p)}{1.47(V_d - m)} - \left[\frac{5.87V_d(2.93t_6 + L_p)}{1.47d_3(V_d - m)}\right]^{\frac{1}{2}} \right\}
$$

Hassna et al. Model [27]

$$
\text{PSD}_c = 2.93V_d(t_6 + h) \\
t_6 = p_a + t_5 - \frac{d_L}{1.38V_d}(t_6 + 2h) \\
t_6 = -h + \sqrt{\frac{h^2 + 5.88V_d\left[L_p + L_i + 1.44(2V_d - m)\right]}{1.47d_3(V_d - m)}} \\
\Delta_c = L_p + 1.47V_d(t_6 + h) \\
\text{PSD}_c = 2.93V_d(t_6 + h), \Delta_c \leq 0 \\
\text{PSD}_c = 2.93V_d(t_6 + h), \Delta_c \geq 0
$$

Van Valkenburg and Michael model [28]

$$
\text{PSD} = 230 \text{ m for } V = 50 \text{ km/h} \\
\text{PSD} = 365 \text{ m for } V = 70 \text{ km/h} \\
\text{PSD} = 575 \text{ m for } V = 110 \text{ km/h}
$$

Rilett et al. model [29]

$$
\text{PSD}_{\text{complete}} = 1.47V_{\text{crit}}t_5 + \frac{1.47at_5^2}{2} + 1.47V_d(t_5 + t_6) \\
\text{PSD}_{\text{short}} = 1.47V_{\text{crit}}p_a + 1.47V_{\text{crit}}t_5 - \frac{1.47at_5^2}{2} + 1.47V_{\text{min}}b_5 + d_3 + 1.47V_0(p_a + t_5 + t_6)
$$

American Association of State Highway and Transportation Officials-AASHTO Green Book [30]

$$
\text{PSD} = d_1 + d_2 + d_3 + d_4 \\
d_1 = \frac{t_5}{2}(V - m - \frac{d_2}{2}) \\
d_2 = \frac{1}{2\sqrt{V_d}} \\
30 \text{ m} \leq d_3 \leq 90 \text{ m} \\
d_4 = d/2d_2
$$
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:

$$y = ax^2 + bx$$

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

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

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

(Figure 3. Passing sight distance (PSD) models comparison.)
\[
\frac{d^2y}{dx^2} = 2a \quad \text{therefore} \quad a = \frac{\Delta i}{2L} 
\]  

(5)

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

\[
y = \frac{\Delta i}{2L}x^2 + i_1x 
\]  

(6)

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

\[
x_A = -\frac{i_1}{\Delta i}L 
\]  

(7)

\[
y_A = -\frac{i_1^2}{2\Delta i}L 
\]  

(8)

the relationship of the curvature is:

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

(9)

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

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

(10)

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

(11)

\[
R_A = \frac{L}{\Delta i} 
\]  

(12)

The minimum radius of curvature \( R_v \) is located at point A, therefore we can assume \( R_v = R_A \).

Let \( D = \text{PSD} \) (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 \( \Delta i \) 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 \( (D = \text{PSD} < L) \). Using the geometric parameters in Figure 4, it results in [22]:

\[
\begin{align*}
    h_1 &= a p^2 \\
    h_2 &= a q^2 \\
    D &= p + q = \frac{1}{\sqrt{a}} \left( \sqrt{h_1} + \sqrt{h_2} \right) \\
    L &= \frac{\Delta i \cdot D^2}{2(h_1 + h_2 + 2\sqrt{h_1 \cdot h_2})} \\
    R_v &= R_A = \frac{L}{\Delta i} = \frac{D^2}{2(h_1 + h_2 + 2\sqrt{h_1 \cdot h_2})} 
\end{align*}
\]

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 \( \Delta i \).

3.2. Case in Which \( D > L \)

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

\[
\begin{align*}
    h_1 &= a \cdot p^2 + 2 a \cdot p \cdot m_1 \\
    h_2 &= a \cdot q^2 + 2 a \cdot q \cdot m_2 \\
    m_1 &= \frac{h_1}{2 a \cdot p} - \frac{p}{2} \\
    m_2 &= \frac{h_2}{2 a \cdot q} - \frac{q}{2} \\
    D &= m_1 + L + m_2 = \frac{h_1}{2 a \cdot p} + \frac{h_2}{2 a \cdot (L - p)} + \frac{L}{2} 
\end{align*}
\]

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

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

then

\[
\begin{align*}
    p &= \frac{L}{1 + \frac{h_2}{\sqrt{h_1}}} \\
    q &= L - p = p \cdot \frac{\sqrt{h_2}}{\sqrt{h_1}} 
\end{align*}
\]

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

\[
\begin{align*}
    D &= \frac{L}{2} + \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \\
    L &= 2 \left( D \cdot \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \right) 
\end{align*}
\]
1,100,024 vehicles, respectively. The sum of the vehicles falling into these three classes is 6,700,663, provided by the Italian guideline (h

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.

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 Infrastructures [10,11]. 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.

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].

\[
R_v = R_A = \frac{2}{\Delta i} \left( D - \frac{h_1 + h_2 + 2\sqrt{h_1 h_2}}{\Delta i} \right)
\]

(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 \( \Delta i \).

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.

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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.

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![Figure 5. Absolute frequency distribution of passenger cars heights.](image)
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 \( \Delta R_v \) 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 (\( \Delta R_v \)) 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).](image)

![Figure 7. \( R_v \) values (\( h_1 = 1.10 \) m and \( h_{2(m)} = 1.48 \) m).](image)

![Figure 8. \( \Delta R_v \) between \( R_v \) values calculated for \( h_{2(15)} = 1.39 \) m and \( h_{2(m)} = 1.48 \) m.](image)
Figure 9. $\Delta R_v$ between $R_v$ values calculated for $h_2 = 1.10 \text{ m} \ [10]$ and $h_2(15) = 1.39$.

Figure 10. $\Delta R_v$ between $R_v$ values calculated for $h_2 = 1.10 \text{ m} \ [10]$ and $h_2(15) = 1.48 \text{ m}$.

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 $\Delta t$, 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 $H_v > 0$. 

\[ H_v = \frac{1}{2} \frac{m}{\Delta t} (v^2 - u^2) + \frac{1}{2} \frac{m}{\Delta t} (v^2 - u^2) + \frac{1}{2} \frac{m}{\Delta t} (v^2 - u^2) + \frac{1}{2} \frac{m}{\Delta t} (v^2 - u^2) \]
Assuming once again that the vertical curve follows a parabolic shape, we can easily infer the function $H_v = H_v(t)$:

$$y_p = bx - ax^2$$  \hspace{1cm} (29)$$

in which:

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

therefore:

$$y_p = i_1x - \frac{\Delta i}{2L}x^2$$  \hspace{1cm} (30)$$

the driver’s line of sight equation is:

$$y_r = mx + n$$  \hspace{1cm} (31)$$

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

$$y_r = y_p \Rightarrow i_1x - \frac{\Delta i}{2L}x^2 = mx + n$$  \hspace{1cm} (32)$$

$$(i_1 - m)x - \frac{\Delta i}{2L}x^2 - n = \frac{\Delta i}{2L}x^2 - (i_1 - m)x + n = 0$$  \hspace{1cm} (33)$$

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

$$\Delta = b^2 - 4ac \Rightarrow (i_1 - m)^2 - 4 \frac{\Delta i}{2L}n = 0$$  \hspace{1cm} (34)$$

$$\left(i_1 - m\right)^2 = \frac{4\Delta i}{2L}n$$  \hspace{1cm} (35)$$

$$i_1 - m = \sqrt{\frac{4\Delta i}{2L}n} \Rightarrow m = i_1 - \sqrt{\frac{4\Delta i}{2L}n}$$  \hspace{1cm} (36)$$

For the abscissa $x$, $y_r$ is

$$y_r = AB + BC$$  \hspace{1cm} (37)$$

$$y_r = \left(i_1 - \sqrt{\frac{4\Delta i}{2L}n}\right)x + n = \left(i_1x - \frac{\Delta i}{2L}x^2\right) + h_1$$  \hspace{1cm} (38)$$

with

$$AB = \left(i_1x - \frac{\Delta i}{2L}x^2\right)$$  \hspace{1cm} (39)$$

$$BC = h_1$$  \hspace{1cm} (40)$$

$$x = v \cdot \Delta t$$  \hspace{1cm} (41)$$

$$\left(i_1 - \sqrt{\frac{4\Delta i}{2L}n}\right)v \cdot \Delta t + n - i_1 \cdot v \cdot \Delta t + \frac{\Delta i}{2L} \cdot v^2 \cdot \Delta t^2 - h_1 = 0$$  \hspace{1cm} (42)$$

$$n - \sqrt{\frac{4\Delta i}{2L}n \cdot (v \cdot \Delta t)} + \frac{\Delta i}{2L} \cdot v^2 \cdot \Delta t^2 - h_1 = 0$$  \hspace{1cm} (43)$$

Then, we found $n$ and $y_r$.

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

$$H_v = BC = AC - AB = h_2 - (y_r - y_p)$$  \hspace{1cm} (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 $\Delta H_v$ 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, $\Delta H_v$ 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).](image)

**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 $\Delta i$.

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 \( h_{2(15)} = 1.39 \text{ m} \), 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 \( h_2 = 1.10 \text{ m} \) 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
- \( d_i \) subinterval of PSD (depending on the model in Table 2)
- \( d \) deceleration rate of passing vehicle abortion
- \( D \) available sight distance
- \( \Delta_c \) 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
- \( \Delta_i \) total grade change
- \( k \) traffic density
- \( L \) crest vertical curve length
- \( L_p \) length of passing vehicle
- \( L_i \) length of impeding vehicle
- \( m = \Delta v \) difference in speed between passing and impeding vehicles
- \( \text{PSD} \) passing sight distance
- \( q \) traffic flow rate
- \( R_v \) crest vertical curves radius
- \( \text{SSD} \) stopping sight distance
- \( t \) time
- \( v \) design speed in \( \text{m/s} \)
- \( V \) design speed in \( \text{km/h} \)
- \( v_s \) mean space speed

**References**

1. Wang, Z.; Liu, C. Critique on the Highway Vertical Curve Design Specifications in China. In Proceedings of the ICCTP 2010: Integrated Transportation Systems: Green, Intelligent, Reliable, Beijing, China, 4–8 August 2010; pp. 3564–3571. [CrossRef]
2. Mohammed, A.A.; Ambak, K.; Mosa, A.M.; Syamsunur, D. A review of the traffic accidents and related practices worldwide. Open Transp. J. 2019, 13, 65–83. [CrossRef]
3. Bhandari, S.B.; Nalmpantis, D. Application of various multiple criteria analysis methods for the evaluation of rural road projects. Open Transp. J. 2018, 12, 57–76. [CrossRef]
4. Mansouri, M.; Kargar, M.J. Analysis and monitoring of the traffic suburban road accidents using data mining techniques; a case study of Isfahan Province in Iran. Open Transp. J. 2014, 8, 39–49. [CrossRef]
5. Royal-Dawson, F.G. Vertical Curves for Roads; E. & F.N. Spon, Limited: London, UK, 1946.
6. Lamm, R. *Highway Design and Traffic Safety Engineering Handbook*; McGraw-Hill Education: New York, NY, USA, 1999.

7. Guerrieri, M.; Ticali, D. Sustainable mobility in park areas: The potential offered by guided transport systems. In *ICSDC 2011: Integrating Sustainability Practices in the Construction Industry*; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 661–668. [CrossRef]

8. Bonnett, C.F. *Practical Railway Engineering*; Imperial College Press: London, UK, 2005.

9. Rogers, M.; Enright, B. *Highway Engineering*; Wiley: New Delhi, India, 2017.

10. Italian Guidelines for the Design of Road Infrastructures (D.M. 5/11/2001): Italy. 2001. Available online: https://www.mit.gov.it/mit/mop_all.php?p_id=1983 (accessed on 3 November 2020).

11. Italian Guidelines for the Design of Road Intersections (D.M. 19/04/2006): Italy. 2006. Available online: https://www.mit.gov.it/mit/mop_all.php?p_id=13799 (accessed on 3 November 2020).

12. Llorca, C.; Tsui Moreno, A.; Garcia, A. Modelling vehicles acceleration during overtaking manoeuvres. *IET Intell. Transp. Syst.* 2016, 10, 206–215. [CrossRef]

13. Ivan, J.N.; Wang, C.; Bernardo, N.R. Explaining two-lane highway crash rates using land use and hourly exposure. *Accid. Anal. Prev.* 2000, 32, 787–795. [CrossRef]

14. Road Accidents in Italy (Years 2000–2006). Available online: www.istat.it (accessed on 1 June 2020).

15. Campbell, J.L. *Human Factors Guidelines for Road Systems*, 2nd ed.; TRB: Washington, DC, USA, 2012; Volume 600.

16. Guerrieri, M.; Corriere, F.; Parla, G.; Ticali, D. Estimation of pollutant emissions from road traffic by image processing techniques: A case study in a suburban area. *ARPN J. Eng. Appl. Sci.* 2013, 8, 668–676.

17. Mauro, R. *Traffic and Random Processes: An Introduction*; Springer: Cham, Switzerland, 2015.

18. Guerrieri, M.; Mauro, R. Capacity and safety analysis of hard-shoulder running (HSR). A motorway case study. *Transp. Res. Part A Policy Pract.* 2016, 92, 162–183. [CrossRef]

19. Mauro, R.; Branco, F.; Guerrieri, M. Contribution to the platoon distribution analysis in steady-state traffic conditions. *Period. Polytech. Civ. Eng.* 2014, 58, 217–227. [CrossRef]

20. Transportation Research Board. *Highway Capacity Manual (HCM2016)*, 6th ed.; TRB: Washington, DC, USA, 2016.

21. Yang, L.; Li, X.; Guan, W.; Zhang, H.M.; Fan, L. Effect of traffic density on drivers’ lane change and overtaking maneuvers in freeway situation—A driving simulator-based study. *Traffic Inj. Prev.* 2018, 19, 594–600. [CrossRef][PubMed]

22. Esposito, T.; Mauro, R. *Fondamenti di Infrastrutture Viarie*; Hevelius: Benevento, Italy, 2003.

23. Swiss Association of Road Specialists (VSS). *Design, Fundamentals, Sight Distances*; Swiss Norm SN 640 090 640 090a; Swiss Association of Road Specialists: Zurigo, Switzerland, 1996.

24. SETRA. *Ministere de l’Equipement, Direction Des Routes (1994), Amenagement des Routes Principales*; SETRA: Paris, France, 1994.

25. Lieferman, E.B. Model for calculating safe passing sight distances on two-lane rural roads. *Transp. Res. Rec.* 1982, 869, 70–76.

26. Glennon, J.C. New and improved model of passing sight distance on two-lane highways. *Transp. Res. Rec.* 1988, 1195, 132–137.

27. Hassan, Y.; Easa, S.M.; Abd El Halim, A.O. Passing sight distance on two-lane highways: Review and revision. *Transp. Res. Part A Policy Pract.* 1996, 30, 453–467. [CrossRef]

28. Van Valkenberg, G.W.; Michael, H.L. Criteria for no-passing zones. *Highw. Res. Rec.* 1971, 366, 1–9.

29. Rilett, L.R.; Hutchinson, B.G.; Whitney, M. Mechanics of the Passing Maneuver and the Impact of Large Trucks. *Transp. Res. Part A 1990*, 24, 121–128. [CrossRef]

30. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*; AASHTO: Washington, DC, USA, 1994.

31. Findley, D.J.; Schroeder, B.; Cunningham, C.; Brown, T. *Highway Engineering: Planning, Design, and Operations*; Butterworth-Heinemann: Oxford, UK, 2015.

32. Italian Car Population, 2006. Available online: http://www.aci.it/ (accessed on 20 June 2020).

33. AASHTO. *A Policy on Geometric Design of Highways and Streets*; AASHTO: Washington, DC, USA, 2001.

34. Guerrieri, M.; Corriere, F.; Rizzo, G.; Lo Casto, B.; Scaccianoce, G. Improving the sustainability of transportation: Environmental and functional benefits of right turn by-pass lanes at roundabouts. *Sustainability* 2015, 7, 5838–5856. [CrossRef]
35. Eriksson, E.; Blinge, M.; Lövgren, G. Life cycle assessment of the road transport sector. *Sci. Total Environ.* **1996**, *189*, 69–76. [CrossRef]

36. Maheshwari, P.; Khaddar, R.; Kachroo, P.; Paz, A. Dynamic Modeling of Performance Indices for Planning of Sustainable Transportation Systems. *Netw. Spat. Econ.* **2016**, *16*, 371–393. [CrossRef]

37. AASHTO. *Policy on Geometric Design of Highways and Streets 2011*; AASHTO—American Association of State Highway and Transportation Officials: Washington, DC, USA, 2011.

38. Mauro, R.; Guerrieri, M. Comparative life-cycle assessment of conventional (double lane) and non-conventional (turbo and flower) roundabout intersections. *Transp. Res. Part D Transp. Environ.* **2016**, *48*, 96–111. [CrossRef]

39. Corriere, F.; Guerrieri, M.; Ticali, D.; Messineo, A. Estimation of air pollutant emissions in flower roundabouts and in conventional roundabouts. *Arch. Civ. Eng.* **2013**, *59*, 229–246. [CrossRef]

40. Azeez, O.S.; Pradhan, B.; Shafri, H.Z.M.; Shukla, N.; Lee, C.-W.; Rizeei, H.M. Modeling of CO emissions from traffic vehicles using artificial neural networks. *Appl. Sci.* **2019**, *9*, 313. [CrossRef]

41. Thomas, N.E.; Hafeez, B.; Evans, A. Revised design parameters for vertical curves. *J. Transp. Eng.* **1998**, *124*, 326–334. [CrossRef]

42. Pu, Z.; Li, Z.; Ke, R.; Hua, X.; Wang, Y. Evaluating the Nonlinear Correlation between Vertical Curve Features and Crash Frequency on Highways Using Random Forests. *J. Transp. Eng. Part A Syst.* **2020**, *146*, 04020115. [CrossRef]

43. Harwood, G.W.; Mason, J.M.; Brydia, R.E.; Pietrucha, M.T.; Gittings, G.L. *Intersection Sight Distance*; Report 383; TRB: Washington, DC, USA, 1996.

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