8th International Conference on Traffic and Transportation Studies
Changsha, China, August 1–3, 2012

Passing Maneuver: Models, Surveys and Simulation
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Abstract

Head-on collisions cause more serious consequences of some types of accidents. These collisions are often due to an error of passing maneuver, on two-lane highways. The latest Italian official statistics for the year 2010 (ACI 2011b) indicate that the proportion of accidents caused by these maneuvers is only 6.5% of total. The consequences of these car accidents unlike are always very serious and the mortality rate is the highest with a value of 4.6 (Relationship between the number of deaths and the number of accidents multiplied by 100). The driver may made a wrong passing maneuver due to insufficient visibility distance. The Passing Sight Distance (PSD) has always been as subject of studies and research (Harwood et al., 2008, NCHPR 2005). These works underline two series of factors that influence the PSD mainly: the first is the size and performance of vehicles, the second is the driver responses to environmental stimuli. This paper presents a study on the differences in some current procedures and guide-lines used to estimate minimum PSD requirements for highway design. The research starts from a review of current design rules (in Italy and U.S.), and continues with an analysis of some classic PSD models, with field studies of passing maneuvers on two-lane highways and with a survey of characteristic data of passenger cars. A data collection by video recordings was used to study some factors influencing the distance value as the actual speed and acceleration of vehicles. This survey was completed with another collection data on physical characteristics and maximum performance of the passenger cars sold in Italy. At the end showed an analysis of different models of proposed PSD and discussion in order to obtained results.

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Key Words: passing sight distance; passing model; speed; acceleration; survey; sight distance; road safety

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1. Introduction

This paper show a first analysis of the minimum PSD needed for the correct passing maneuver on two-lane highways. In this paper analyzed only two main models of the passing maneuver: the first model with a constant difference of speed between passing and passed vehicle (Flying passing, CNR 1973, 1980 and MIT 2002), the second model with the passing vehicle that accelerates while it changes lane (Accelerative passing, AASHTO Green Book (2004) and MUTCD 2009). The speeds of the vehicles, the accelerations and the lengths of them are used for calculate the minimum PSD. For the second model of passing maneuver (accelerative model) it was considered that the driver could accelerate even in a different way by the original AASTHO model.

The work starts from an investigation on road of the real passing maneuvers. The survey has provided the characteristic values for about 100 passing maneuvers. Have built a database with car models sold in Italy from the years 2004 to 2010. For passenger cars were considered the size and performance characteristics (speed and acceleration). The measured values were split on engine displacement classes and the percentages of the survey samples were compared to the same percentage classes of Italian vehicle fleet.

We realized a simulation software for the random extraction of vehicles with physical characteristics and performance typical of different displacement classes in the real fleet. For each extraction the program has provided values of three different vehicles that could realize the overtaking maneuver or not. The same sets of congruent values were used to calculate the minimum PSD for all the proposed models.

The aim of this work was to obtain a first critical comparison among the values of the PSD according to the different computational models, the values acquired with the road survey and the model that has given the best results with simulation data.

2. Passing maneuver models

Two different basic models have been used for the definition of PSD. The first has been chosen by Italian rules (Flying passing, CNR 1973, 1980 e MIT 2002), the second is the U.S. model (Accelerative passing, AASHTO Green Book 2004).

2.1. Flying passing

The flying passing model has been adopted in Italy and has always been the same since the years seventies. According to rules the minimum PSD is equal to the sum of the product of the speed of the passing vehicle for the sum of the times needed to do three steps of the passing maneuver (see Figure 1): in a first step the vehicle (A) moves on the opposite lane and must start to passing the vehicle on his right, in a second step the vehicle (A) passes this vehicle and in last step the passing vehicle return on its lane. The safety minimum condition considers that a vehicle running in the opposite lane (C) has covered the same distance at the same speed of the passing vehicle in this same total time.

The calculation assumptions are:
- the passing vehicle run at uniform speed equal to that of oncoming vehicle in the opposite lane;
- the passed vehicle run at slower speed than passing vehicle.

Given that:

$$ PSD = 2 \cdot v \cdot (t_1 + t_2 + t_3) = 20 \cdot v $$

where $PSD =$ passing sight distance (m); $v =$ speeds of the passing vehicle (m/sec); $t_1 =$ time for passing vehicle to moves on the opposite lane equal to 4 sec; $t_2 =$ passing time equal to 2 sec; $t_3 =$ time for passing vehicle to return on its lane equal to 4 sec.
Passing time is:

\[ t_2 = \left( \frac{L_1 + L_2}{\Delta_v} \right) \]  

(2)

where \( t_2 \) = time of the passing maneuver (sec); \( L_1 \) = length of passing vehicle (m); \( L_2 \) = length of passed vehicle (m); \( \Delta_v \) = difference between the speed of vehicles (m/s).

The factors that affect the PSD value are the speed of the passing vehicle, speed of passed vehicle and lengths of vehicles.

2.2. Accelerative passing

Also this design criterion is essentially unchanged from the criterion established in the years fifties by AASHO. The minimum PSD is the sum of the following four distances (Fig. 2):

\[ PSD = d_1 + d_2 + d_3 + d_4 \]  

(3)

where, PSD = passing sight distance; \( d_1 \) = distance traveled during perception and reaction time and during initial acceleration to the point of encroachment on the left lane; \( d_2 \) = distance traveled while the passing vehicle occupies the left lane; \( d_3 \) = distance between passing vehicle and opposing vehicle at the end of the passing maneuver (as safety margin); \( d_4 \) = distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or 2/3 of \( d_2 \).
The calculation assumptions are:

- the passed vehicle travels at uniform speed;
- the passing vehicle reduces speed and trails the passed vehicle as it enters the passing section;
- when the passing section is reached, the passing driver requires a short period of time to perceive the clear passing section and to begin to accelerate;
- passing is accomplished under what may be termed a delayed start and a hurried return in the face of opposing traffic. The passing vehicle accelerates during the maneuver, and its average speed during the occupancy of the left lane is 16 km/h (10 mph) higher than that of the passed vehicle;
- when the passing vehicle returns to its lane, there is a suitable clearance length between it and any oncoming vehicle in the other lane.

Given that:

\[
d_1 = t_1 \cdot \left( v - \Delta_v + \frac{a \cdot t_1}{2} \right) \tag{4}
\]

\[
d_2 = t_2 \cdot v \tag{5}
\]

where \( t_1 \) = time of initial maneuver (sec); \( v \) = average speed of passing vehicle (m/sec); \( \Delta_v \) = speed difference of passed vehicle and passing vehicle (m/s); \( a \) = average acceleration (m/sec\(^2\)); \( t_2 \) = time of occupation of the left lane.

An interpolation of the values given in the AASTHO tables furnish the relationships in order to the times required during the first and second phases of the maneuver and the acceleration as function of the average passing speed in m/sec:

\[
t_1 = 0.074 \ v + 2.50 \tag{6}
\]

\[
t_2 = 0.166 \ v + 6.75 \tag{7}
\]

\[
a = 0.004 \ v + 0.57 \tag{8}
\]

Basically the factors that affect the PSD, for a flat roads, are: (i) speeds of the passing vehicle, of the passed vehicle and of the vehicle coming in the opposite direction; (ii) vehicle dimensions; (iii) headway between vehicles, which depends on the speed; (iv) skill and reaction time of the driver; (v) acceleration of passing vehicle.

3. Road survey

Figure 3 shown a satellite picture of the survey road chosen. We was examined the road section (Fig. 4) by placing six targets at a fixed distance of 20 m for a total measured base of 120 m. The width of each lane was 4.70m with a lateral shoulder of 0.30 m. We took record movies in three different days for a total of two hours and with the acquisition of 101 passing maneuvers.
For the running vehicles and for those who have completed the passing maneuver we have registered: the transit number, the transit times on all the bases, the speed and acceleration between markers for passing and passed vehicles. In case of passing maneuver was also evaluated the safety distance between opposite vehicles on the same lane through the speed of opposite vehicle and its transit time on the first marker.

We observed 71 regular maneuvers of passing, 12 irregular maneuvers with unsafe passing; 18 maneuvers were unclassified. The main results obtained are shown in Table 1. In Fig. 5 shows the accepted PSD as function of speed differences between the vehicles: the trend line have a slightly negative angle. Figure 6 shows the trend of the average acceleration of the passing vehicle on the next target lines.

The result analysis (Table 1) shows that:
- the average acceleration of the passing vehicle is about 0.60 m/sec² and the driver continues to accelerating the car for more than 60 m from the start of passing maneuver;
- the speed difference between the vehicles that pass is high and about of 25 km/h;
- the headway between passing vehicles is about 1.5 sec;
- the accepted passing distance is considerably less than that calculated with the Italian rules for the average speed of the passing vehicle indicated in Table 1 (for about 75 km/h, PSD is about 400 m).

| Table 1. Survey results | Mean | St. Dev. | V. Coeff. | 85º perc. |
|-------------------------|------|----------|-----------|-----------|
| Passing speed (km/h)    | 74,52| 10,21    | 0,14      | 85,71     |
| Max passing acceleration (m/sec²) | 0,57 | 0,85   | 1,50      | 1,29      |
| Passed speed (km/h)     | 49,62| 11,02    | 0,22      | 62,04     |
| Speed diff. between vehicles (km/h) | 24,89 | 13,05 | 0,52 | 37,92 |
| Headway (sec)           | 0,98 | 0,87     | 0,89      | 1,53      |
| Headway (m)             | 19,15| 15,92    | 0,83      | 29,69     |
| PSD (m)                 | 241,21| 125,50   | 0,52      | 386,09    |
maximum speed, acceleration between 0 and 100 km/h, pickup between 70 and 100 km/h. The survey results for more than 500 models are shown in Table 2.

The Italian vehicle fleet in the year 2010 was obtained from report ACI (2011a). The class 0-800 and the class 800-1200 were joined in the only class 0-1200. The percentages of the classes of the engine displacement compared to total number of passenger cars are shown in Table 3 and Fig. 6. The values of these percentages have been used in order to the random generation of the vehicle sets.

5. Data simulation of passing maneuvers

The software for random vehicle generation furnishes for each extraction three different and independent vehicles as members of engine displacement classes indicated. The probability of extraction for a some class of passenger car compared to other class is proportional to the percentage specified in Table 3. For each class, the extractions were made hypothesizing a normal distribution the characteristics of the vehicles (length, speed, acceleration) with the mean and standard deviation indicated in table 2.

Among the different sets of three passenger cars extracted were chosen those who have a speed difference between the passing and passed vehicles at least of 5 m/s and those who have the speed of the opposite vehicle not greater than that of the passing vehicle. We used 100 set from 600 total extractions. The characteristic distribution values of the extractions used in the models are shown in Table 4.

Table 2. Passenger car survey results

| Classes               | Values       | Mean   | Std. Dev. | Var. Coeff. | 85° perc. |
|-----------------------|--------------|--------|-----------|-------------|-----------|
| Class 0 - 1200 cc     | Veh. Length (m) | 3.54   | 0.17      | 0.05        | 3.70      |
|                       | Max Speed (km/h) | 153.41 | 7.82      | 0.05        | 161.65    |
|                       | Acceleration 0-100 km/h (m/sec²) | 1.89   | 0.25      | 0.13        | 2.12      |
|                       | Pickup 70-100 km/h (m/sec²) | 0.69   | 0.32      | 0.46        | 1.04      |
| Class 1200 - 1600 cc  | Veh. Length (m) | 4.00   | 0.30      | 0.08        | 4.34      |
|                       | Max Speed (km/h) | 176.56 | 16.77     | 0.09        | 192.89    |
|                       | Acceleration 0-100 km/h (m/sec²) | 2.38   | 0.46      | 0.19        | 2.72      |
|                       | Pickup 70-100 km/h (m/sec²) | 0.78   | 0.24      | 0.30        | 1.00      |
| Class 1600 - 2000 cc  | Veh. Length (m) | 4.45   | 0.24      | 0.05        | 4.71      |
|                       | Max Speed (km/h) | 200.60 | 19.14     | 0.10        | 224.83    |
|                       | Acceleration 0-100 km/h (m/sec²) | 3.00   | 0.98      | 0.33        | 3.44      |
|                       | Pickup 70-100 km/h (m/sec²) | 1.02   | 0.50      | 0.49        | 1.42      |
| Class 2000 - 2500 cc  | Veh. Length (m) | 4.56   | 0.21      | 0.05        | 4.75      |
|                       | Max Speed (km/h) | 198.95 | 34.52     | 0.17        | 223.96    |
|                       | Acceleration 0-100 km/h (m/sec²) | 2.84   | 0.54      | 0.19        | 3.24      |
|                       | Pickup 70-100 km/h (m/sec²) | 1.20   | 1.03      | 0.86        | 1.76      |
| Class over 2500 cc    | Veh. Length (m) | 4.72   | 0.25      | 0.05        | 4.96      |
|                       | Max Speed (km/h) | 242.98 | 40.04     | 0.16        | 292.62    |
|                       | Acceleration 0-100 km/h (m/sec²) | 4.22   | 1.43      | 0.34        | 5.55      |
|                       | Pickup 70-100 km/h (m/sec²) | 2.26   | 1.14      | 0.51        | 3.20      |
6. Models adopted

Basically have been used the two models mentioned above. The calculation parameters have been replaced by the results of random extractions.

For the model Flying passing (FPM) has been used the speed of the passing vehicle and its length, the speed of the passed vehicle and its length, the speed of the vehicle on the opposite lane. In the two versions (FPM_1 and FPM_2) has been used the average of the headways detected by experimentation in the first step and third step of maneuver. For the model FPM_1 has been used fixed average headway (distance) in meters. For the model FPM_2 has been used fixed average headway (time) in seconds.

For the model accelerative passing (APM_0) has been used the relationships (4) and (5) with the values obtained from the relationships (6), (7) and (8).
More have been modified the accelerative passing models with three different steps of acceleration (greater than the basic model APM_0 and equal to the distances \(d_1, d_2\) and \(d_3\) of Figure 1) most adequate to results of road survey. Has been investigated the behaviour of the models in acceleration. In the model APM_1 the passing vehicle follows the vehicle that has to pass at same speed and then the passing vehicle accelerates until to start of the passing maneuver; passing vehicle completes maneuver at constant speed. In the model APM_2 passing vehicle accelerates more until full passing of the vehicle on the right and then completes maneuver at constant speed. In the model APM_3 the passing vehicle completes the whole maneuver accelerating.

For the all simulations of the accelerative passing models the initial speeds of passenger cars (passing and passed vehicles) were the same. The results are reported in Table 5.

7. Results considerations and further developments

This first work has been useful for checking some assumptions of two classical passing models (FPM_0 and APM_0) compared to the real behavior of the driver. These two models of the PSD give both very high values in order to provide the road safety.

Initial results show that the model FPM_2 furnishes results closer to experiment reality. On other hand the model APM_00 remains rather rigid. The three proposed models (APM_1, APM_2 and APM_3) seem to adapt better to experimental data than the original APM_00 model.

The values of the random extractions (Table 4) are greater than those given by road survey (Table 2). Any way the value of 85° percentile of the passing speed coincides with the value of 85° percentile of operating speed obtained on rural roads (Capaldo et al. 1997).

In any case, the parameters that most seem to affect the results were, in addition to speeds and accelerations of the vehicles, also the vehicle headways at the start and end of the maneuver.

The prosecution of the work must realize a more extensive experimental data base with greater emphasis to the headway measures.

The software for random generation of the vehicle characteristics and performances should be enhanced to consider also the driver characteristics: is necessary to characterize not only vehicles with engine displacement classes but also the drivers with the passing capacity (for example low, medium, high). This driver classification will affect partially the random performances of the vehicle.

Finally have considered only passing maneuvers among passenger car: other passing maneuvers should be explored with different kind vehicles.

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