



Determination of minimum horizontal curve radius for safe stopping sight distance of vehicles overpassing truck platoons

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Abstract

In the last few years, the importance of trucks on inland cargo transportation has not stopped increasing. Meanwhile, truck platooning is emerging, along with automated driving, to reduce costs using new technologies. In this context, this research aims to provide a first study on the effects of truck platoons on freeways' road safety, focusing on the reduction of visibility caused by truck platoons with shorter gaps on horizontal curves. This safety issue will also affect motorways and multilane roads. A geometric model has been developed and computed, which provides the available sight distances and the stopping sight distance (SSD) for a vehicle overpassing a platoon in a circular curve without transition curves. There are many variables, such as radius, lane width, vehicle and truck platoon parameters, and relative position. The overpassing vehicle has been included in the model for both human-driven and automated, considering the adaptive cruise control radar cone of visibility. The main result of this study is the minimum curve radius in order to allow a safe SSD, considering different design criteria. Moreover, depending on the level of automation of the vehicle, this minimum radius will be different, being higher for automated vehicles. Results prove the importance of the studied phenomenon and the necessity to implement further countermeasures. Additionally, a case study where the effects of truck platooning on the visibility of a real motorway stretch are evaluated.

1 | INTRODUCTION

The concept of coupling different vehicles virtually has existed since the beginning of driving automation (Sheikholeslam & Desoer, 1990). However, it has been in recent years when it has really become possible. For that reason, different development programs were started in different countries and by different manufacturers. These

programs include previous ones such as PATH (Bergenheim et al., 2012) in the United States or SARTRE (Robinson et al., 2010) in the European Union, or other ones such as ENSEMBLE (van Vliet et al., 2018; Willemssen et al., 2018) or the SCANIA platooning project (Bergenheim et al., 2012). All of them have different approaches to platooning, offering different technologies, infrastructure requirements, or traffic integration

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(Bergenheim et al., 2012). While some of them consider mixed traffic platoons (Robinson et al., 2010), other platooning approaches focus on heavy vehicles, providing not only an increase in road safety but also a decrease in costs (Bergenheim et al., 2010). In this case, this research focuses on truck platooning, being understood as small convoys of freight vehicles using virtual coupling (Janssen et al., 2015).

Transportation represents more than 5% of Europe's gross domestic product (Janssen et al., 2015). Therefore, transportation is the basis of current economies. In particular, road transportation means more than 70% of all transport and has more than 10 million employees within the European Union. Industrially, it means more than 75% of industrial transportation and more than 2200 billion tonne-kilometer yearly (Brizzolara & Toth, 2016). Therefore, there has been an increasing interest in the creation of smart corridors, which could take most of the existing technologies to improve the logistics industry (Oonk, 2016; Tavasszy & Janssen, 2016).

Truck platooning is often divided into three different levels (Janssen et al., 2015), moving between SAE automation levels 2 to 4 (SAE, 2016). Considering a two-truck platoon where the leading truck is human-driven (HD), level 1 would be a situation where the first platoon would be human-driven and the second one would follow automatically requiring the second driver to keep its attention on driving. Level 2 considers a human-driven truck followed by a truck with a resting driver. Level 3 would be the case where there would be no driver on the following truck at all. Level 1 is about to be implanted, tests having already been carried out. Levels 2 and 3 are not expected until 2025 or 2030 (Janssen et al., 2015).

Economically, truck platoons offer huge advantages. Driver efficiency could be considerably increased, gaining up to 30% productivity (Jacob & Arbeit de Chalendar, 2018; Tavasszy & Janssen, 2016), although an important training process would have to be applied prior to its introduction (Shladover et al., 2015). In addition, it could help in reducing the driving shortage (Brizzolara & Toth, 2016). With truck platooning technology, traveling with much shorter gaps, fuel consumption reductions have been estimated to be 8%–13% for the following vehicle and 2%–8% for the leading vehicle (A. Alam, 2014; Robinson et al., 2010). Being the origin of 24% of gas greenhouse emissions, fuel consumption reduction could also be an important environmental advantage (Brizzolara & Toth, 2016; Vegendla et al., 2015; Zhaodong Wang et al., 2015).

If the focus is set on road safety, however, blind spots can be found. While some studies assume an increase on road safety due to automation (Janssen et al., 2015), other researchers have noticed a possible safety reduction due to the effect on the visibility of trucks traveling together with



FIGURE 1 Visibility reduction due to trucks traveling together

reduced gaps (Janssen et al., 2015; Jacob & Arbeit de Chalendar, 2018).

Having time gaps as low as 0.3 s (Janssen et al., 2015), truck platooning allows much more reduced gaps than conventional trucks traveling together. This means that an overtaking vehicle's vision will not only be obstructed by one of the trucks while overtaking but by the whole truck platoon, meaning a longer time with a reduced available sight distance (ASD). Considering truck platoons could be longer than 50 m (Janssen et al., 2015), they could have an important impact on visibility. This safety issue mainly arises along carriageways with at least two lanes in the same direction (freeways, motorways, and multilane roads).

In addition to all of these, the overtaking vehicle might be automated-driven. It uses radar to detect objects in their line-of-sight, but there is a range for detection with a visibility maximum distance, and the radar also has a limited field of view, defined by the opening angles in azimuth and elevation in which they can scan the environment (cone of visibility). Therefore, radar might have a great impact on visibility, thus reducing it even more. Some issues related to cybersecurity when coupling different autonomous vehicles (AVs) together have also been found (Wang et al., 2019).

ASD is the length of the roadway ahead that is visible to the driver. Stopping sight distance (SSD) is, however, the sum of the distance traversed during the perception and reaction time and the distance to brake the vehicle to a stop (AASHTO, 2018). In order to keep road safety standards, SSD should always be lower than ASD. The effect of truck traveling together on visibility can be seen in Figure 1. It can be seen how, despite not being a truck platoon, there is a great visibility reduction. With truck platoons, this reduction will be even higher due to the smaller gap.



This research focuses on how a truck platoon has an effect on an overpassing vehicle's ASD in freeway right-turn curves taking into consideration different parameters. Moreover, automated vehicles have different limitations, so a special case study has been considered taking into account the limitations of the radar to detect objects. ASDs will be calculated and compared with corresponding required SSDs. Also, the comparison is done for different parameters as radius or lane width in order to check how visibility is reduced in different conditions.

Additionally, results have been applied to a real Spanish motorway with a high volume of heavy traffic. This way, the reader will be able to verify how important the safety impact of truck platooning would be if no other measures are proposed.

Truck platooning is only one among the multiple research lines which have been followed in the field of intelligent transportation systems. In this sense, truck platooning relies on multiple previous research, which involves not only the automation of the vehicles but also new possibilities for infrastructure.

Regarding the automation of vehicles, lateral control has been continuously developing since the 1990s (O'Brien et al., 1996; Netto et al., 2004) and is still continuously developing. Recent research in this field has focused on lane-changing maneuvers (Mirchevska et al., 2018) and the study of mixed environments (Zhen Wang et al., 2020; Wang et al., 2020). Last, different research has been made focusing on how a self-driving car radar characteristics affect safety (Ma et al., 2019). Truck platoons are expected to coexist with human-driven vehicles, so the study of mixed environments is of high importance. Regarding the automation of truck platoons itself, there is multiple recent research that involves both research institutions and truck manufacturers (Ellwanger & Wholfarth, 2017; Patole et al., 2017; Taylor et al., 2020).

The effect and opportunities of automation on the traffic flow have also been deeply studied. In this sense, Kesting and Treiber (2008) modeled the involved parameters in traffic flow, and Jiang and Adeli (2004) focused on the analysis and forecasting of the traffic flow. Computational technologies have been applied to study the particularities of the traffic flow such as road incidents or working zones (Adeli & Ghosh-Dastidar, 2004; Adeli & Karim, 2005; Hooshdar & Adeli, 2004). Platooning of vehicles when overpassing a work zone has also been recently studied (Cao et al., 2021). Regarding truck platooning, its affection for traffic flow has been a popular concern in the last few years. In this sense, different authors have been working and continue working on this research topic (Bergenheim et al., 2012; Calvert et al., 2019; Li et al., 2015; M. Wang et al., 2019). The risk of spreading malicious information has also been considered (P. Wang et al., 2019).

As mentioned, truck platooning would allow reducing gaps between trucks and therefore a reduction in fuel consumption. To evaluate the extent of this reduction, several researches have been carried out in the last 10 years (Abdolmaleki et al., 2019; A. Alam, 2014; Robinson et al., 2010; Vegendla et al., 2015; Zhaodong Wang et al., 2015; Zhang et al., 2020).

Focusing on this research topic—visibility, different research has been carried out. Models to determine sight distance in particular conditions were developed in the late 1990s (Hassan et al., 1995; Lovell, 1999). However, this research has not been updated in the last few years to include new parameters—such as radar's field of view or cone of visibility—and new road components—such as truck platoons. In this sense, only recent models, which focus on the conditions of the road itself such as its readiness, have considered the particularities of AVs (Gouda et al., 2020).

Up to date, there is little research on how platoons affect visibility. Only a few researchers have collaterally focused on this issue. In this sense, Zhang et al. (2020) and Yang et al. (2018) defend the need to carry out further research on how road geometry could be improved in order to allow truck platoons safely. van Zaanen (2018) also referred to the necessity to determine the factors that should be taken into account to achieve that goal. Additionally, Alsghan et al. (2019) focus on the sign occlusion problem that trucks platoons may provoke.

In this context, the novelty of this research lies in both the topic itself—the effect of truck platoons to visibility in curves has not been studied before—and the consideration of both human-driven and automated overpassing cars. Therefore, the study provides the necessary results to evaluate not only the effect of truck platoons on road safety but also how this affection changes depending on the overpassing car's characteristics and limitations. Results include the minimum radius so a truck platoon may be driven on an existing road keeping current safety levels. This way, results are not only of current interest but can also be directly applied as proved in the case study.

For our purpose, the methodology that has been followed in order to obtain ASD in each situation is first explained. After that, results will be presented, discussed, and applied to a case study. Finally, some relevant conclusions will be presented.

2 | METHODS

For the achievement of the research goal, a geometric model was developed. The model considers a highway right-turn curve where a passenger car is overpassing a platoon (Figure 2). For the proposed model, the truck platoon

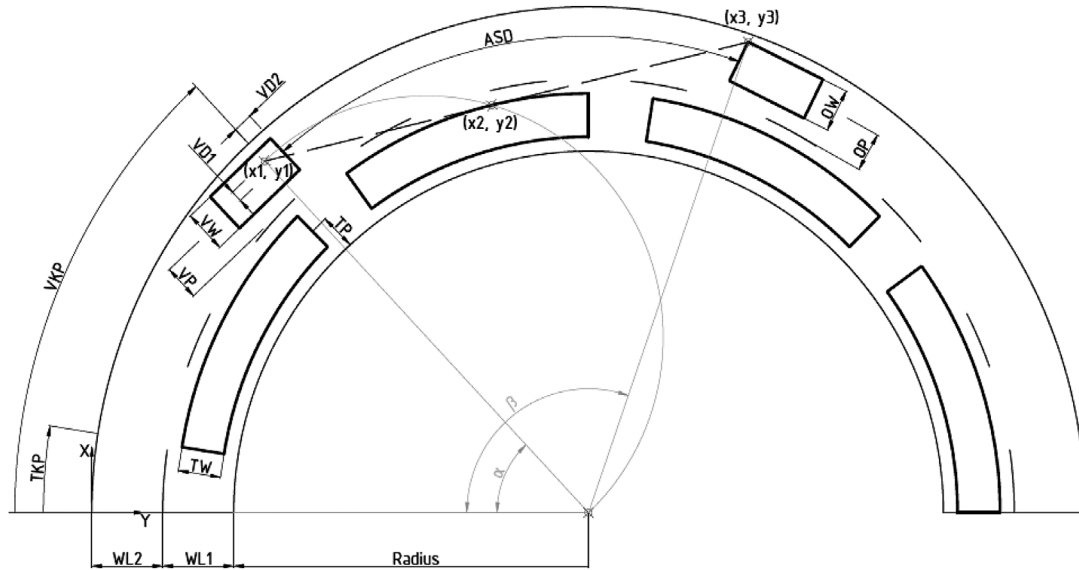


FIGURE 2 Model parameters for human-driven overpassing car

has been initially modeled as a long single truck, meaning that no visibility has been considered between trucks. This can be done because trucks traveling on platoons have very short gaps that visibility through them is much reduced. To determine the accuracy of that assumption, an upgraded model including the existing gap between trucks has also been developed. This will also allow studying the influence of the gap in the visibility reduction. Additionally, platooning has been modeled as if it was circled. Usual high curve radius along freeways, compared to the reduced size of trucks means that error related to this simplification will be minor. The geometrical model is conditioned by multiple variables, which are defined in Table 1 and Figure 2.

There are two additional values that refer to the station where the overpassing vehicle (VKP) and the truck platoon (TKP) are placed. Stations are measured on the curve's outer line. TKP is defined by the rear part where the first visible truck is, whereas VKP is defined as the station where the driver is. In this case, they do not influence ASD but are used in the model as preconfigured values.

Different geometric models have been developed. First, the model where the overpassing car is human-driven is presented. Then, the model where the overpassing car is automated-driven will be presented. This second model consists of the human-driven model with some extra limitations due to radar parameters. Both of them have been developed using a Cartesian coordinate system as seen in Figure 2. Angles have been calculated with centesimal degrees (gon). Furthermore, an additional model has also been created to determine the increase of visibility thanks to the gap between trucks.

TABLE 1 Model parameters

Parameter	Definition
WL1	Width of the inner line
WL2	Width of the outer lane
Radius (R)	Curve radius
TW	Truck platoon width
TP	Distance between truck platoon's axis and inner edge line
VW	Overpassing vehicle width
VP	Distance between overpassing vehicle's axis and center line
VD1	Distance between overpassing vehicle's axis and driver's position
VD2	Distance between overpassing vehicle's front bumper and driver's position
OW	Obstacle width
OP	Distance between obstacle's axis and center line
ASD	Available sight distance

2.1 | Human-driven overpassing car

First, the model calculates the driver position (x_1, y_1) . For that, it intersects the circumference where the driver position is with the line, which goes from the curve center to the driver's position (Equation 2). This line is calculated thanks to the angle α that is turned between the truck platoon's position and the overpassing vehicle's position (Equation 1):

$$\alpha = \frac{(VKP - TKP) * 400}{2\pi * (R + WL1 + WL2)} \quad (1)$$

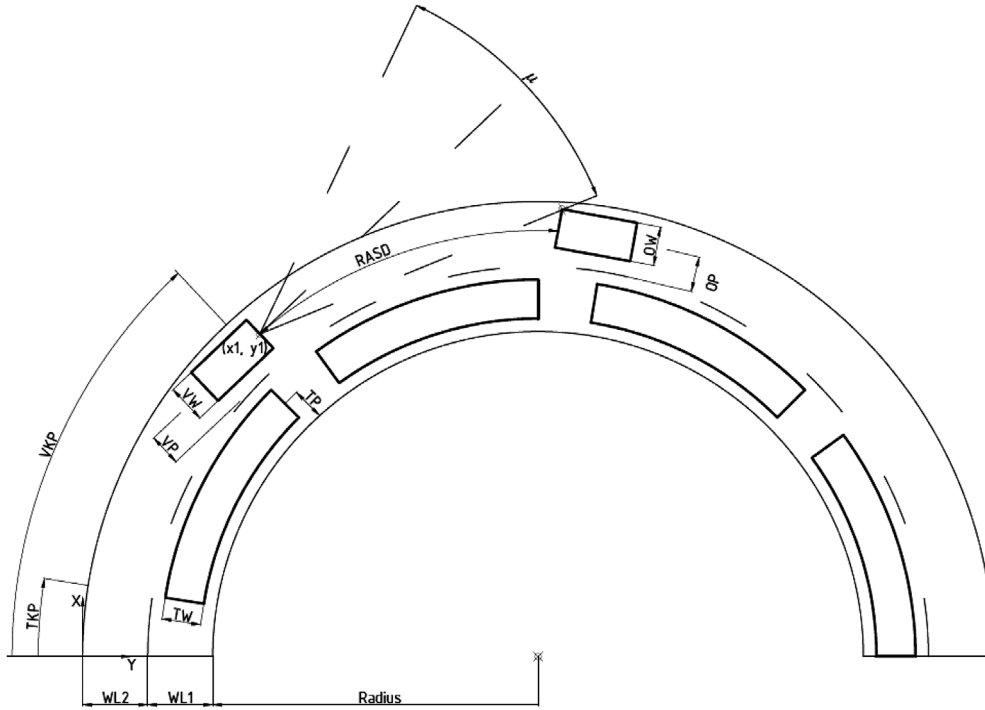


FIGURE 3 Model parameters for automated-driven overpassing car, conditioned by radar's cone of visibility

$$\begin{cases} x1^2 + (y1 - (R + WL1 + WL2))^2 = (R + WL1 + VP + VD1)^2 \\ y1 = \tan\left((100 - \alpha) * \frac{2\pi}{400}\right) * x1 + R + WL1 + WL2 \end{cases} \quad (2)$$

After that, the truck platooning tangent point, which limits visibility $(x2, y2)$, is calculated. This is done by intersecting the truck platooning external circle equation and the circle whose center is the middle point of the line, which goes from the driver's position to the curve's center and whose radius is the distance between that point and the curve's center point (Equation 3). Thus, the tangent point is calculated by using the isoptic curve properties:

$$\begin{cases} x2^2 + (y2 - (R + WL1 + WL2))^2 = \left(R + TP + \frac{TW}{2}\right)^2 \\ \left(x2 - \frac{x1}{2}\right)^2 + \left(y2 - \left(\frac{R + WL1 + WL2 - y1}{2} + y1\right)\right)^2 \\ = \left(\frac{x1}{2}\right)^2 + \left(\frac{R + WL1 + WL2 - y1}{2}\right)^2 \end{cases} \quad (3)$$

The straight line from $(x1, y1)$ to $(x2, y2)$ is intersected with the circumference, which defines the first obstacle visible point $(x3, y3)$; Equation 4):

$$\begin{cases} \frac{x3 - x1}{x2 - x1} = \frac{y3 - y1}{y2 - y1} \\ x3^2 + (y3 - (R + WL1 + WL2))^2 = \left(R + WL1 + VP + \frac{OW}{2}\right)^2 \end{cases} \quad (4)$$

Having calculated all these previous points, ASD can be calculated. First, the turned angle between the driver's

position $(x1, y1)$ and the obstacle's first visible point $(x3, y3)$ is calculated. For that, the turned angle between both points is needed. The turned angle between TKP and VKP has already been calculated (α ; Equation 1). The turned angle between TKP and $(x3, y3)$ is calculated from the slope of the straight line that goes from $(x3, y3)$ to the curve center point (β ; Equation 5).

$$\frac{x - x3}{x3} = \frac{y - y3}{(R + WL1 + WL2) - y3} \rightarrow \text{Slope} \rightarrow \beta \quad (5)$$

Knowing both α and β , ASD would be as shown in Equation (6). As ASD is measured from the front part of the vehicle, VD2 has to be subtracted from the result:

$$ASD = \frac{2\pi * (R + WL1 + VP) * (\beta - \alpha)}{400} - VD2 \quad (6)$$

In this way, ASD for any human-driven passenger car is calculated.

2.2 | Automated-driven overpassing car

In the case of considering an automated-driven car, ASD might be the same. But it may also be that ASD is limited by the visible length (VL) from the mounted radar or by the radar's cone of visibility or field of view (μ ; Figures 3 and 4). Because of that, all the equations presented for the



TABLE 2 Parameter values

Parameter	Value (m)
VW	2.10
VD1	0.45
VD2	2.20
TP	1.75
TW	2.60
OW	2.10
OP	1.65

$$\begin{cases} \frac{x7-x4}{x5-x4} = \frac{y7-y4}{y5-y4} \\ x7^2 + (y7 - (R + WL1 + WL2))^2 = \left(R + WL1 + VP + \frac{OW}{2}\right)^2 \end{cases} \quad (15)$$

Having calculated all these previous points, ASD can be calculated as it was calculated in the human-driven model. Being based on Equations (5) and (6), the only difference is that the driver's position is now $(x6, y6)$ instead of $(x1, y1)$, and the obstacle's first visible point is now $(x7, y7)$ instead of $(x3, y3)$. In this way, maximal ASD is calculated and the influence of the separation on visibility may be studied.

3 | RESULTS

As said before, different models have been developed that provide different results, which, despite being similar, differ in the basic points. For that reason, results will be presented separately.

3.1 | Human-driven overtaking car

In the case of having a human-driven overtaking car, multiple simulations have been developed. In all, some of the parameters considered in the model have been considered as fixed parameters. These include overtaking vehicle width (VW), distance between overtaking vehicle's axis and driver's position (VD1), distance between overtaking vehicle's front bumper and driver's position (VD2), truck platoon width (TW), and obstacle width (OW), with their values determined according to Green Book (AASHTO, 2018). These values can be seen in Table 2.

For this simulation, lane width has been considered as a variable. Values between 3.3 and 3.6 have been introduced, being always $WL1$ equal to $WL2$. In addition to that, two cases have been considered for each lane width. The first one considers that all the vehicles involved in the study are placed in the center of the corresponding lane ($VP = TP = OP = WL/2$).

Another case has been studied for each lane width, where both the truck platoon and the obstacle are placed in the center of the corresponding lane ($TP = OP = WL/2$). In this case, the overtaking vehicle has been assumed to be placed slightly to the left of the lane. This is done because overtaking vehicles tend to keep as far as possible from the overtaken vehicle. Because of that, VP has been defined in this case as shown in Equation (16):

$$VP = \frac{\frac{WL}{2} - \frac{VW}{2}}{2} \quad (16)$$

Having defined all the values of the variables, different study cases have been calculated. In all of them, simulations have been carried out with curve radius as the main variable, taking values from 250 to 4550 m, with 100 m intervals. Results are shown on the right part of Figure 6, where the calculated ASD depending on the curve radius is seen. Different results deriving from different lane widths are shown in diverse line styles. If overtaking vehicle position has been considered to be in the center of the lane (first case), the line is shown as a darker line. In the second case, where the overtaking vehicle is moved from the center of the lane to the left, it is always represented with a brighter line and defined as modified vehicle position for the different lane widths considered. In total, eight different simulation cases have been run.

For example, if visibility for a lane width of 3.5 m (continuous green line) and a radius of 1250 m is checked, the ASD would be approximately 170 m. If priority is set on what the design speed should be in this case to keep safety standards, it is required to go left from the point (1250, 170) until the black line is obtained. In this case, the design speed would have to be 95 km/h or lower in order to maintain safety requirements.

From that first result, a second figure has been developed, which combines both sides of Figure 6. This has been made by estimating what the design speed should be in order to keep ASD equal to the required SSD so as to keep safety standards. Thus, a new graphic is obtained, which shows what the design speed should be depending on the curve radius and the different lane width study cases (Figure 7). Additionally, a dotted line can also be seen, which shows what the required speed (design speed) depending on the radius (conditioned by the geometry of the road) would be if there were no reduction in visibility.

Thanks to this figure, if the previous example (radius of 1250 m and lane width of 3.5 m) is taken again, it could be directly checked that the required design speed would be 95 km/h. In addition, this graphic can also be used to compare it with the required speed if there were no effect on visibility. In the example that is being checked, the usual

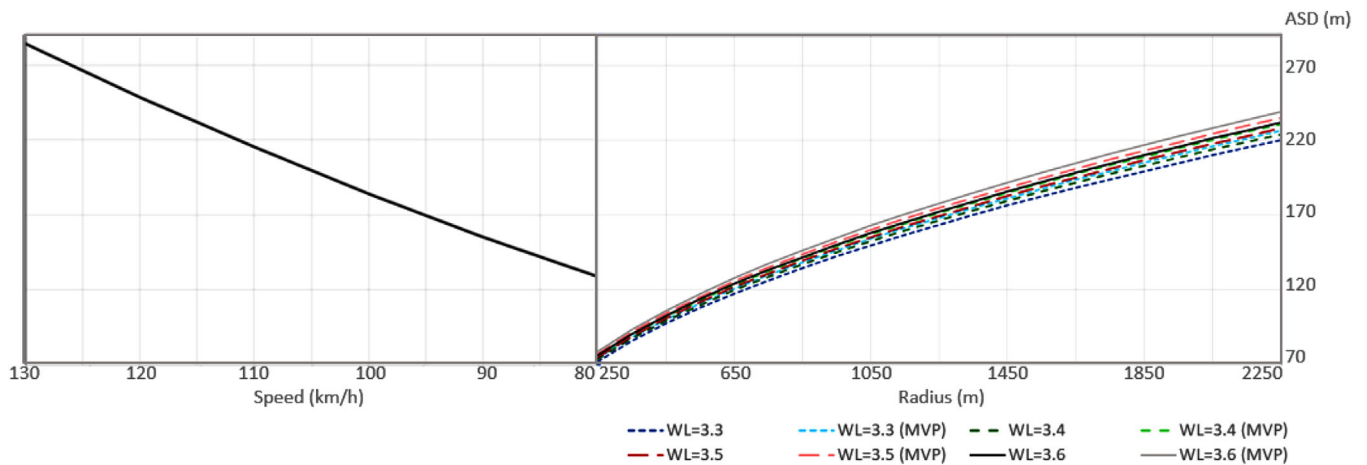


FIGURE 6 Human-driven case visibility

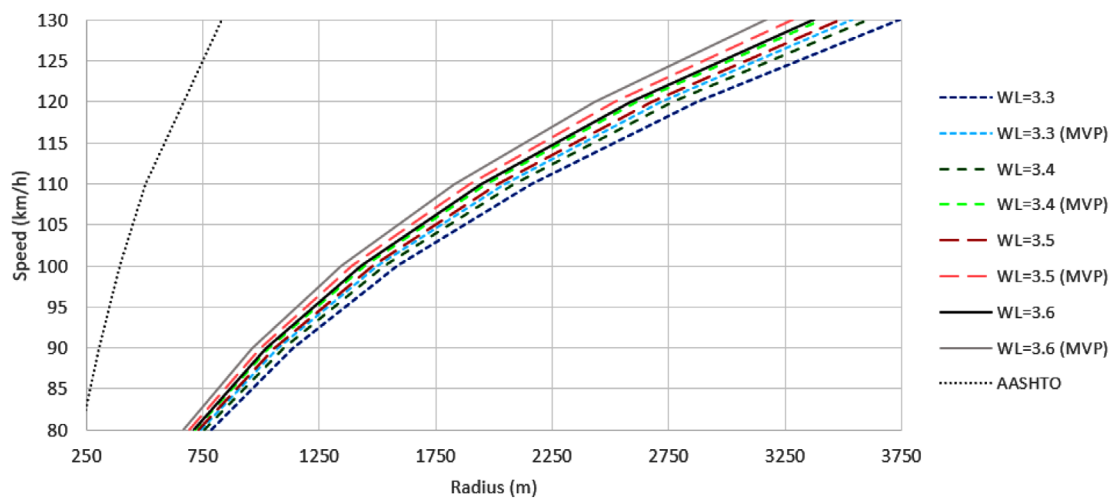


FIGURE 7 Human-driven case visibility: Required speed for stopping sight distance

design speed for a 1250 m radius would be over 130 km/h if there were no truck platoon.

3.2 | Automated-driven overtaking car

As seen before, automated-driven overtaking cars have extra visibility limitations due to radar restrictions; thus, results might also differ.

In the case of having an automated-driven overtaking car, multiple simulations have also been developed. As before, some of the parameters considered in the model have been considered as fixed parameters. These include VW, VD1, VD2, TW, and OW, with their values determined according to Green Book (AASHTO, 2018) as shown in Table 2. In this case, lane width has been considered to be a constant parameter of value 3.5 m. This has been made because lane width impact has been considered to be already measured within the human-driven case. The

same occurs with the vehicle-modified position case previously considered. Additionally, there are other parameters affecting specifically the automated-driven case, which have been considered as having more interest than lane width: radar's VL and cone of visibility, which have been considered as variables.

Radar's parameters have been determined according to recent research (Patole et al., 2017) and currently available products on the market (Arbe Robotics, 2020; Tesla, 2019). Currently available radar's capabilities depending on radar's detection range are shown in Table 3.

According to existing data and considering that ASD mainly depends on long-range radars, radar's VL has been considered to vary between 100 and 300 m, with increases of 20 m. Besides, radar's cone of visibility has been assigned with different values between 5 and 30 centesimal degrees. Initially, it had been considered with increases of 5 centesimal degrees. Nevertheless, due to the obtained results, it was decided to do an extra simulation considering an angle



TABLE 3 Radar capabilities

Detection range	Long	Medium	Short
Range (m)	Up to 300	Up to 150	Up to 40
Azimuthal field of view (gon)	±15	±40	±90

Note: Parameters are defined in Table 1.

of 7.5 centesimal degrees. In this case, 70 simulations have been tested.

Once all parameters are defined, different simulations were made. These have provided as results ASD depending on the radius. They are represented on the upper-right graphic in Figure 8. Different line styles mean different angles as shown.

In addition, different length limitations can be appreciated through the horizontal limit lines. Angles of over 20 centesimal degrees have been decided to be represented together, as they provide the same results. Furthermore, sight distance's values of more than 240 m have not been represented to ensure clarity. This may be done because their influence on discussion is minimum as will be seen.

In the upper-right part of Figure 8, three different kinds of lines depending on what the limiting factor for visibility is can be seen. Horizontal lines mean visibility is limited by radar's visibility length. Inclined straight lines mean visibility is limited by radar's cone of visibility. Curved lines, which are highlighted with a wider thickness, mean that

visibility is conditioned by the truck platoon. In order to facilitate the interpretation, the required SSD by Green Book (AASHTO, 2018) has been represented in the same figure on the upper-left side by a continuous line (Figure 8) depending on speed. Required SSD depends on perception-reaction time (PRT). As PRT may vary depending on the radar system, different required SSDs are shown depending on the radar's PRT. Considering smaller PRT than for the human-driven model, speed will be higher.

Additionally, the design speed depending on radius if there were no visibility effect has been decided to be represented in the same figure. This has been done in the lower-right part of Figure 8. This way, we are able to compare what the required speed would be with and without a truck platooning.

For example, if a curve with a 1250 m radius, a cone of visibility of 15 centesimal degrees, and a VL of 180 m is considered, ASD would be 162 m and conditioned by the truck platoon. Taking a PRT of 0.5 s, the maximum safe speed would be 113 km/h. If there were no truck platoon at that point, the design speed would have been over 130 km/h. Instead, if a cone of visibility of 5 centesimal degrees is considered, ASD would be 117 m and conditioned by the cone of visibility, and maximum safe speed would be 97 km/h.

Related to radar's cone of visibility, a second figure has been developed (Figure 9). In this case, the required radius, so that visibility is not limited by radar's cone of visibility, is shown depending on the cone of visibility itself. That means that for a particular radius, if the cone of visibility

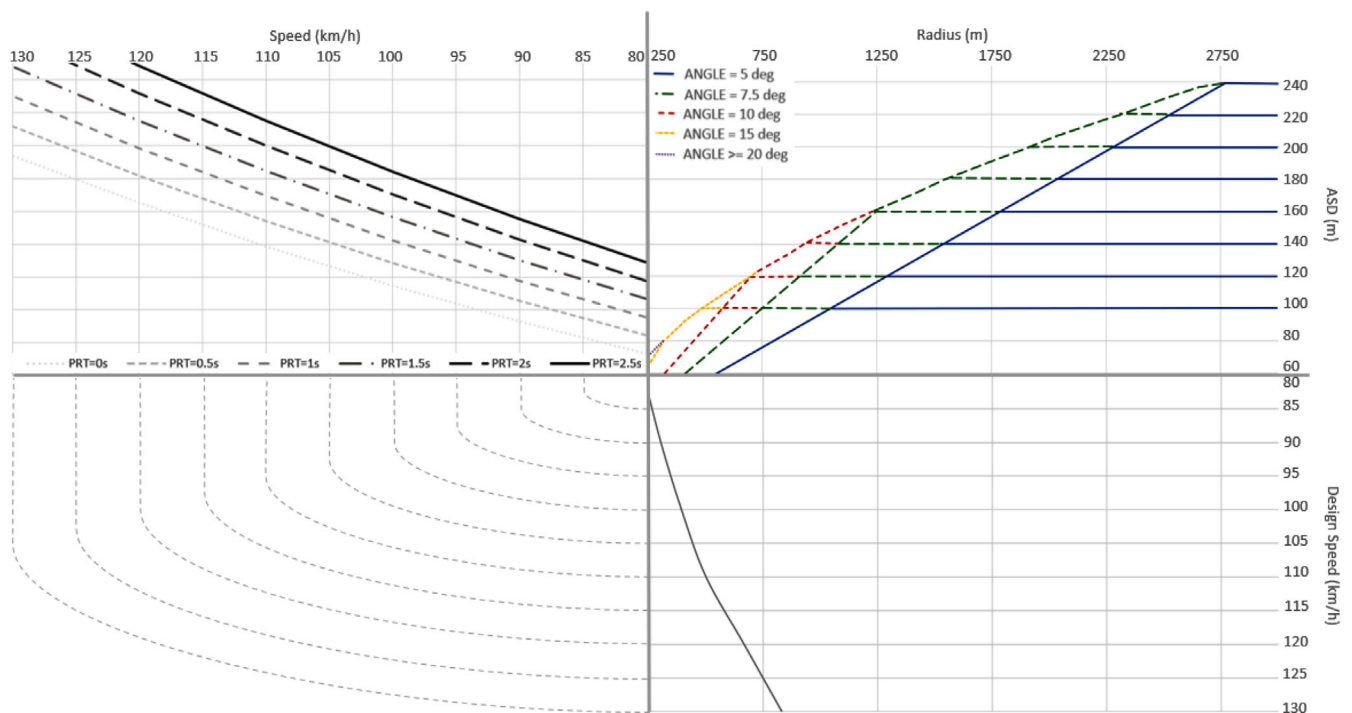


FIGURE 8 Automated-driven case visibility

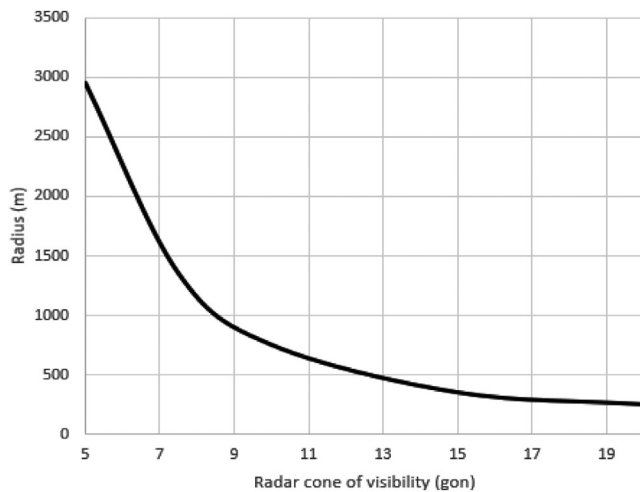


FIGURE 9 Automated-driven case: Required radius for truck platooning visibility reduction

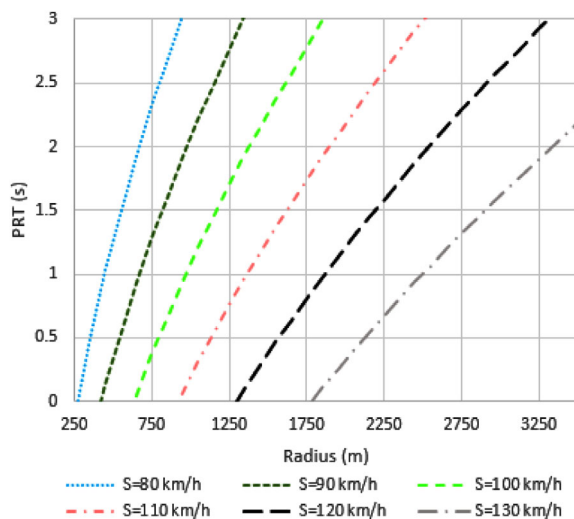


FIGURE 10 Required perception-reaction time depending on speed and radius

is higher than shown, the visibility would not be affected. If it is lower, however, it will have an effect on visibility. In this case, the truck platoon would not be a limiting factor to visibility.

If, for example, the 1250 m radius that was considered previously is taken, the minimum cone of visibility should be approximately of 8 centesimal degrees. That means that for visibility angles of less than 8, visibility will be conditioned by radar. If not, the truck platoon will condition visibility. That can be easily checked through the three different kinds of lines presented in Figure 8 upper-right graphic.

PRT might be a crucial factor when speaking about automated-driven cars. Therefore, an additional figure has been developed. Figure 10 shows the required PRT for an overtaking car driving in a curve with a given radius and

at different speeds. For example, if an overtaking car is driving in a curve with a radius of 1750 m at 110 km/h, a PRT of 1.75 s of lower is required to ensure the required sight distance. If speed is suddenly increased to 120 km/h, PRT would have to be reduced to 0.85 s so that safety requirements are achieved.

3.3 | Visibility increase due to trucks' platoon gap

This third development case focuses on the influence of the gap between trucks on visibility. In particular, the objective is to estimate the increase of previously calculated visibility due to the existing gap. The gap between trucks has been up to this moment omitted, having calculated visibility as a tangent line to the platoon. The key point here is obtaining and subsequently analyzing the increase of visibility that gaps could provide to discuss its influence on the visibility reduction effect.

To estimate the increase of the previously calculated visibility due to the existing gap, maximum visibility is calculated following the previously explained method. Once carried out, subtraction between maximum visibility and human-driven truck tangent visibility provides the increase of visibility due to the existing gap between trucks forming the platoon.

Parameters' values have been determined according to Green Book (AASHTO, 2018) as shown in Table 2. Lane width is considered to be a constant parameter of value 3.5 m. The additional parameter representing truck length has also been determined according to Green Book (AASHTO, 2018), considering a value of 22.4 m. Moreover, gap between trucks is the main variable for this study case, so multiple values have been considered.

Figure 11 shows the increase of visibility depending on the existing gap between trucks. It takes gaps between 4 and 15 m. This same model has been applied to gaps of up to 50 m as shown in Figure 12. This has been done in order to evaluate its effect, compared to the current situation in the upcoming discussion.

Thus, a gap of 10 m would provide an increase of visibility between 0.2 m—with a radius of 2500 m—and 0.7 m—with a radius of 250 m. If a gap of 40 m is taken, variation would be between an additional VL of 3.3 and 10 m.

4 | DISCUSSION

From the presented results, multiple discussions may appear. Due to the differentiation between the two study cases (human-driven and automated-driven overtaking cars), the significant results that have been obtained are somewhat different. For that reason, the results for both

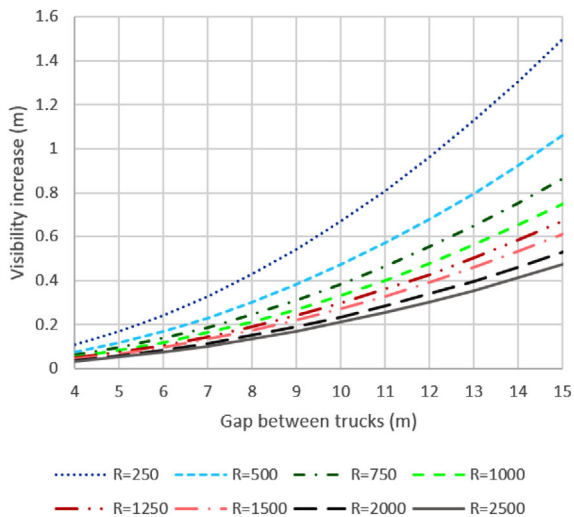


FIGURE 11 Visibility increase due to existing gap between trucks (gap from 4 to 15 m)

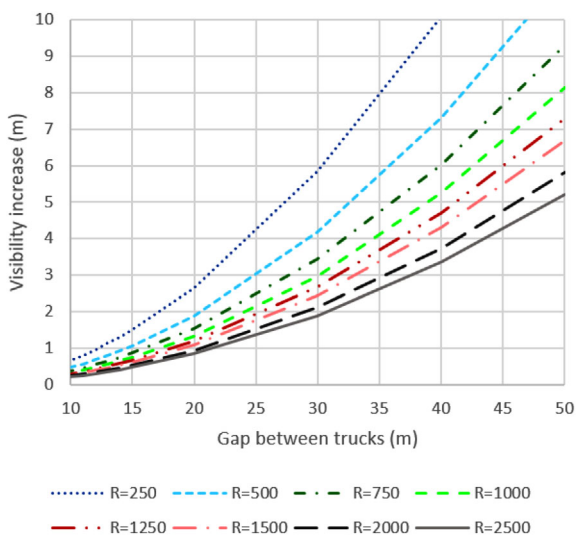


FIGURE 12 Visibility increase due to existing gap between trucks (gap from 10 to 50 m)

study cases will be discussed separately. Nevertheless, being the automated-driven model a derivative from the human-driven model, most of the discussion carried out for the original model may also be applicable for the automated-driven one. Additionally, visibility increase due to the truck's platoon gap has also been discussed separately.

To date, there is a lack of discussion on how visibility might be affected by a truck platoon. Due to that, the aim here is centered on extracting information from the obtained results without having much to compare. However, the general thoughts that are presented here are clear and may be used in the future as the basis for further discussion.

4.1 | Human-driven overpassing car

There are three main lines to discuss from the results obtained in the case of having a human-driven overpassing car. These include the effect of lane width in the visibility obstruction and the effect of the overpassing vehicle position in the visibility obstruction. The key point would be in this case determining how the presence of a truck platoon affects the required speed by AASHTO, compared to the standard design speed if there were no important effect on visibility by the platoon. With that, not only the awareness of how significant the effect on visibility is taken, but we will also see which measures would have to be applied if truck platoons were about to arrive on our roads without any change in the current road design guidelines and road geometries.

Regarding the effect of lane width in road visibility, Figure 7 shows that the effect of increasing lane width has a small change in ASD, compared to ASD itself. In fact, high increases of ASD can only be seen with a really high radius. Knowing that an increase of ASD would specially be useful with a smaller radius, it does not appear that having bigger lane widths would lead to improved road safety. In addition to all that, increasing lane width would be a difficult measure to apply on current roads.

With respect to the effect of the overpassing vehicle position in the visibility obstruction, we can however see how ASD increases are bigger than changing lane width by 0.10 m (Figure 6). That means that without changing the infrastructure, increases in ASD may be significantly beneficial for road safety. The problem is that despite being something many drivers unconsciously do, that is not what regulations could control. Nevertheless, that would be something that may be included in automated-driven systems, which currently focus on keeping themselves centered in the lane (O'Brien et al., 1996; Netto et al., 2004).

The main objective of this paper is studying how truck platoons affect road visibility. Regarding the results previously presented, it can already be said that truck platoons have a great impact on visibility. With a radius smaller than 400 m, the ASD would be even smaller than 100 m. This is far less than what Green Book (AASHTO, 2018) would require for that radius and would mean almost no chance of avoiding crashing with a possible obstacle.

AASHTO provides certain design speeds depending on the curve radius due to geometric restrictions. However, speed might also be limited by visibility, as seen in results. That means that in standard conditions—without truck platoons on the road—design speed will be conditioned by the geometry. Nevertheless, due to the presence of truck platoons, the speed limit would have to decrease in order to keep the required SSD equal to ASD.



It is comparing the design speed without truck platoon to the required speed limit with a platoon that we can actually notice how big the effect on highway visibility conditions is. Data that can be extracted from Figure 7 has been summarized in Table 5. It can be seen that for each radius, the speed limit should be according to Green Book (AASHTO, 2018) considering geometric regulations and what the speed limit would have to be if there were a truck platoon on the road taken into account the visibility limitation. As only used for comparison, speeds have been rounded.

It can be easily seen how due to visibility reduction caused by truck platoons on highways, there is a great decrease in the required speed limit, compared to the standard design speed limited by road geometry. That means, for example, that even for a large radius such as 1000 m, the speed limit would have to be less than 90 km/h, compared with the 130 km/h without truck platoon on the road.

The table also allows to conclude that truck platoons should only be driven on roads with a curve radius of over 2500 m if no changes to the road are expected and safety standards are expected to be high. That means that for roads where truck platoons are planned, a study should have to be carried out on the effect on visibility on any point and, therefore, adapting the road for the platoons. This could only be done in two ways: either making the curve radius higher than 2500 m or reducing the speed limit for the curve radius lower than 2500 m ensuring that ASD equals the required sight distance at all points of the curves. That might require unusual speed limits even under 80 km/h.

While design speed is useful to evaluate the visibility reduction, operating speed might also be used when evaluating the impact on current roads, as it is real-time vehicle speed that characterizes the overtaking maneuver. Additionally, the main difference between geometry-limited speed and visibility-limited speed might confuse drivers, who might perceive the speed limit as extremely restrictive, which may cause frequent violation of speed limits, losing the necessary credibility.

Having confirmed the scale of the problem, exposure time is an important issue. Time exposure is, in fact, the main difference between current trucks and truck platoons. Currently, cars overtaking a truck also suffer from visibility reduction. Nevertheless, while current trucks might have an approximate length of 16 m, a truck platoon would be much longer. Table 4 shows exposure time and overtaking distances for truck platoons with different characteristics. Parameters have been estimated for a differential speed between the truck platoon and the overtaking car of 30 km/h. Thus, it can be easily compared how big the exposure time would be when overtaking a truck platoon.

TABLE 4 Time exposure analysis

No of trucks	Gap (m)	Exposure time (s)	Overtaking dist. (m)
1	–	1.92	64
2	5	4.44	148
2	8	4.80	160
2	10	5.04	168
2	15	5.64	188
3	5	6.96	232
3	8	7.68	256
3	10	8.16	272
3	15	9.36	312

TABLE 5 Required speed depending on radius for the human-driven (HD) and autonomous vehicle (AV) cases

Radius (m)	Geometry limited speed (km/h)	HD platoon limited speed (km/h)	AV platoon speed (km/h)
250	87	<80	<80
500	110	<80	81
750	125	80	98
1000	>130	88	109
1250	>130	95	112
1500	>130	100	118
1750	>130	105	124
2000	>130	110	128
2250	>130	113	>130
2500	>130	117	>130

Even though the overtaking distance is directly related to exposure time, it is a parameter of high importance for the study. Due to the initial stage of the presented research line, the developed model still has some limitations, which have been mentioned before. Among these limitations, the curve has been considered as an infinite circular curve. Thus, the overtaking distance so that the developed model can be applied accurately. Despite this fact, the precision of the model when applied to real highway geometries with transition curves is discussed in the upcoming study case.

Further research is needed in order to specify what the measures have to be in order to allow human-driven truck platoons on the road. These might include a deep study of the road, as said before, but also different measures as dynamic speed limits, which would have to be studied and proposed. Equipping truck platoons with specific lateral lights (on the left) and obstacle detection sensors might also be an option to warn overtaking cars of



FIGURE 13 Dynamic lighting warning system

an upcoming danger (Figure 13). This way they would be able to advise overpassing drivers of an incoming risk with the help of lights and visibility reduction would be compensated.

4.2 | Automated-driven overpassing car

Everything that has been said for the human-driven case is still applicable to this case. Nevertheless, radar limitations imply that further considerations must be taken. In this case, main discussions are related to the influence of radar's VL, radar's cone of visibility, and PRT. Regarding the effect on truck platoons to visibility, the discussion would be almost the same that for the human-driven case, with some particularities regarding the position of the radar.

Radar's VL has a key effect on visibility. As expected, visibility is really conditioned by this parameter (Figure 8). Assuming short PRTs, it is possible that the automated system performs adequately in order to obtain a minimum VL of 170–180 m. Having this minimum visibility, there will be no effect on visibility unless the speed is over 130 km/h. Some manufacturers and developers are already selling their radars for that length. However, most of them do not share or confirm this kind of data, so tests should be carried out in order to ensure safety is guaranteed.

Regarding radar's cone of visibility, Figure 8 shows how important the effect on visibility can be. In Figure 9, we can see what the required radius is so that cone of visibility limitations do not affect visibility. The effect on visibility is higher with smaller cones of visibility, especially when below 10 centesimal degrees. Only with angles of over 20 centesimal degrees, the cone of visibility limitation would not affect visibility. In the case of highways curves, with usually over a 500 m radius, 13 centesimal degrees would be enough. Once more, the lack of information from manufacturers does not help. Most of them do not include the cone of visibility of their radars in the technical specifica-

tion, but it is estimated to be lower in radars with higher VLs.

Research on ASD when using automated-driven cars has already been carried out, concluding that the reduction of visibility when using radars is not negligible (Ma et al., 2019). In addition, the difficulty in finding radars with long VLs and big cones of visibility at the same time might involve the need for further technological development. If the focus is put on the effect of truck platoons on an automated-driven overpassing vehicle, Figure 8 shows how significant the reduction of visibility is. If it is compared with the human-driven case, it can be seen how visibility reduction is even higher. This is due to the radar's position, which in this case is centered in the vehicle's axis. Additionally, automated-driven cars usually drive in the center of the lane, which does not give the opportunity of gaining some extra ASD by positioning to the outer part of the curve.

PRT may be a key factor. It is true that visibility reduction is higher, but PRT will also be lower. That means that required sight distances will also be less. PRTs are currently less than 1 s (Tesla, 2019), being the objective to reach a 0.1 s PRT. Taking a 0.5 s PRT, the required visibility would be 180 m at 120 km/h. For a human-driven car, that distance would have to be 250 m. Different PRT might be required in different situations as seen in Figure 10. Therefore, automated-driven cars should include the possibility of reducing PRT in situations of special risk. This might be done through the reduction of the radar's region of interest in dangerous situations—such as the overpassing maneuver to a truck platoon. This may be done through machine learning techniques and classification algorithms (K. M. R. Alam et al., 2020; Pereira et al., 2020; Rafiei & Adeli, 2017).

Taking into account how visibility differs from the human-driven case, most of the discussion presented before is still applicable to this case. Nevertheless, due to shorter processing times, the required speed limit so that ASD equals the required sight distance will be higher. Previously, the result indicated that with a radius of 1000 m design speed would have to be less than 90 km/h. In this case, taking a 0.5 s PRT, the speed limit could be over 110 km/h. In Table 5, we can see what the platoon-limited speed would be if an automated car with a PRT of 0.5 s was taken. It is clear that if the overpassing vehicle is automated-driven and not conditioned by radar's parameters, the effect of truck platoons on road safety would be much less. But it is essential that radar's parameters do not condition visibility because if they do so, the required speed limit might be even less than in the human-driven case as seen before. In this case, research and studies still have to be carried out to ensure that radar does not limit visibility, and infrastructure would have to be



studied before allowing truck platoons as said for the first case.

4.3 | Visibility increase due to truck's platoon gap

At this point, visibility obstruction has been discussed without considering the existing gap between trucks. Nevertheless, it provides a certain increase in visibility depending on the length of the existing gap. So how does this gap affect visibility?

Figure 11 shows the increase of visibility obtained when the gap between trucks is considered, compared to the truck-tangent visibility discussed before. In this figure, a slight visibility increase can be seen. In this sense, if expected truck platoon gaps are taken—between 4 and 15 m—an increase in visibility would not be of more than 1.5 m. If ASD's order of magnitude is taken—as seen in Figure 6—it can be then said that increase of visibility is negligible for any of the gaps that can be expected for truck platoons. Therefore, the proposed model—which considers visibility as constant and tangent to the truck platoon regardless of the existing gap—can be said to be accurate enough for this research's objective.

Nevertheless, if Figure 12 is studied, for separations that are larger than expected for truck platoons, the visibility increase takes importance. Being aware that actual trucks traveling together drive with much longer distances between them than truck platoons, we can conclude that when introducing truck platoons in current roads, the gap effect on visibility would go from providing a crucial increase of visibility to a negligible one.

To go deeper into this possibility, the current separation between trucks traveling together is studied in the upcoming case study. In this sense, further research on this topic is needed to analyze what new impacts on visibility truck platoons would cause if compared with current trucks traveling together. This must be done taking into account the increasing automation of the vehicle fleet.

5 | CASE STUDY

To show the applicability of the developed research, results have been applied to an existing motorway with high heavy traffic volume (AP-7, Spain). Two different approaches have been followed. First, an observational study of the existing layout of trucks traveling together forming a caravan has been carried out. Afterward, the geometry of the studied stretch of the road with particularly high heavy traffic volume has been studied to assess what the effects of truck platooning on that motorway stretch would be. Addi-

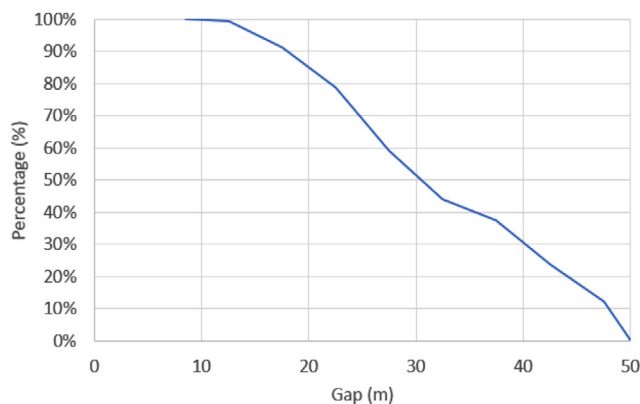


FIGURE 14 Distribution of observed gaps between trucks traveling together as a caravan

tionally, the case study has also been used to evaluate the accuracy of the developed model.

5.1 | Truck caravan's layout

For the study of the truck caravan's layout, aerial images have been used. Thus, 103 groups of trucks have been recorded, having measured 147 separations between trucks. Among all caravans, 44 of them were formed by more than two trucks.

Distance between consecutive trucks has been the main criteria to evaluate whether two trucks are traveling together forming a caravan or not. This way, trucks that are traveling with distances of less than 50 m between them—which equals to a driving time of 2 s at 90 km/h—have been considered to be traveling together.

Once measured, a basic statistical analysis has been carried out. Globally, trucks drive with an average gap of 30.08 m. The minimum recorded distance has been 8.15 m. Figure 14 shows the percentile distribution of gaps.

Meaning an important reduction in separation, compared to existing truck caravans, it can be confirmed that truck platooning would have a significant impact on existing roads. As discussed before, less separation between trucks means less visibility, and less visibility means less road safety.

5.2 | Effects of truck platooning on an existing road

For the assessment of truck platooning effects on an existing motorway, the stretch between AP-2 and A-2 has been analyzed. According to the Spanish Ministry of Transportation (MITMA, 2018), 10,088 heavy vehicles cross that stretch every day. Taking the current speed limits in that

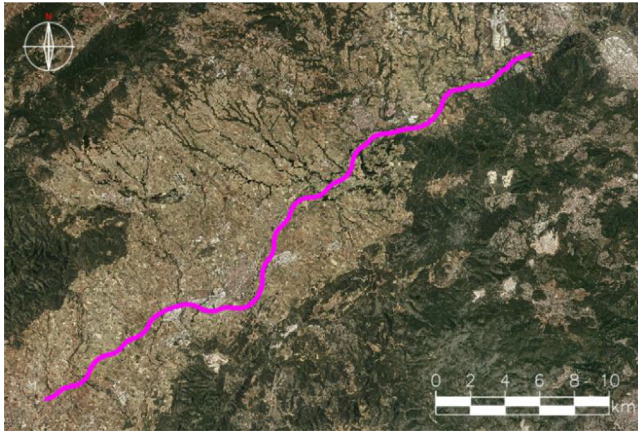


FIGURE 15 Orthoimage and defined polyline

road and assuming that all trucks would travel forming a three-trucks platoon, that would mean a car driving on that road would find a platoon every 80 s. Therefore, the importance of the problem discussed in this research within high-heavy traffic roads is clear. Figure 15 shows the orthoimage of the studied stretch.

Horizontal alignment of the road has been obtained through the methodology proposed by Camacho-Torregrosa et al. (2015). First, a high-detailed aerial image of the area has been obtained. Second, a polyline following the road axis has been drawn using Autodesk® Civil 3D. The polyline was based on 631 points and had a total length of 37,371.1 m (Figure 15). Third, points defining the polyline were exported as text and horizontal alignment was calculated. According to Camacho-Torregrosa et al. (2015), the accuracy of the obtained curvature profile is high enough for research use.

Obtained horizontal alignment is formed by a total of 34 tangents, 40 circular curves, and 73 spiral transitions. Being a major highway built in the 1970s, the result is characterized by having multiple curves with a big radius of up to 4000 m with short or no tangents at all between them.

For the statistical analysis, it has been decided to omit circular curves whose deflection angle is less than 6 gon. This has been done because of their reduced length and effect on driving behavior and visibility. Having discarded these elements, a basic statistical analysis has been carried out. Results are shown in Table 6.

The case study has been used to confirm the accuracy of the developed model. This way, ASD has been obtained through two other methodologies and compared to the results provided by the proposed model.

First, ASD has been estimated using the model proposed by AASHTO's Green Book (AASHTO, 2018). It includes a formula to calculate ASD limited by a sight obstruction placed on the inner part of a highway curve. The given formulation is limited, as it does not consider as many vari-

TABLE 6 Summary statistics

Information	Value
Minimum radius (m)	998.38
Maximum radius (m)	3994.35
Average radius (m)	1402.89
Standard deviation (SD) (m)	61,296
Median (m)	1202.68
Average circular arc length (m)	667
Circular arc length SD (m)	372.85

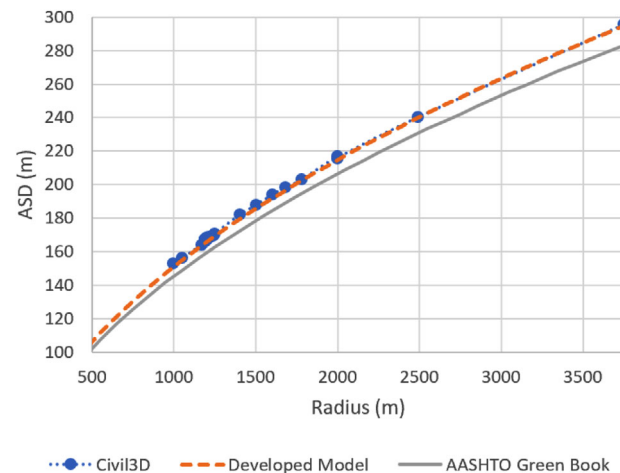


FIGURE 16 Evaluation of the accuracy of the developed model

ables as the proposed model, but may be used to check how more accurate the developed model is.

Second, visibility has been estimated by using the capacities of the Autodesk® Civil 3D software. Given the road alignment (Figure 15), the mentioned software allows to carry out a visibility simulation from the driver's point of view. In this case, simulations consider all main parameters included in the developed model. Because of that, the ASD provided by the software may be considered of high accuracy.

As mentioned, the accuracy of the developed method is compared with the two other methods. Figure 16 shows what available would have to be depending on radius when using the three different methodologies. It should be taken into account that Autodesk® Civil 3D ASD has been obtained from the real studied highway alignment. Therefore, it only offers ASDs for the existing radii (shown by dots).

According to Figure 16, it can be checked that, despite some assumptions being made, the developed model is highly accurate.

Regarding curve length, the studied stretch contains circular arcs with an average length of 667 m. Vehicles overpassing a truck platoon would need a distance of between

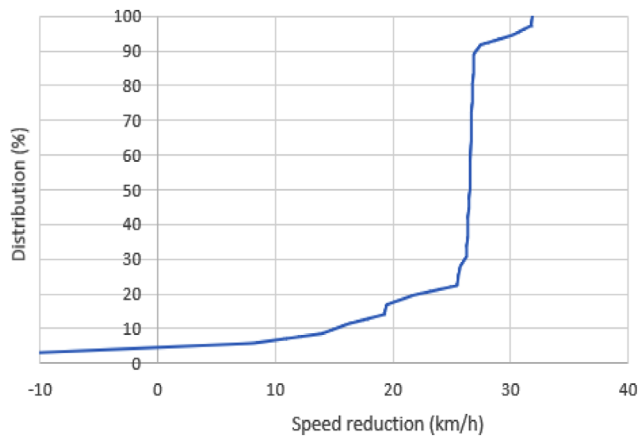


FIGURE 17 Speed reduction distribution depending on curves radii

148 and 312 m (Table 4). Thus, most circular arcs of the studied stretch are long enough to host the complete overtaking maneuver, which proves the applicability of the model despite the fact that it only considers circular curves without transition curves. In any case, the sum of circular arcs and transition curves would be much longer. Additionally, the accuracy of the developed method has already been proved in a real highway stretch through this case study.

Having confirmed the accuracy of the developed methodology, results may be applied to the studied motorway stretch. Regarding Table 6, speed would have to be limited on some of the road's curves for human-driven overtaking cars if truck platoon were to be introduced immediately. Being the current speed limit of that highway of 120 km/h, lower speed limits would have to be applied in curves with a radius of less than 2750 m (Figure 7). Within the studied stretch, 94.6% of circular curves have a radius that is smaller than 2750 m. These radii go from 1000 to 2140 m, which would mean speed limits of between 85 and 110 km/h (Figure 17).

Considering both road directions separately, 47.3% of the road length would have to display reduced speed limits due to the truck platoon effect on visibility on right-turn curves. The effect is equally divided between the two driving directions, as both right and left turns are found in both directions in a proportional distribution.

Considering automated-driven overtaking cars, results are different. As has been seen, automated-driven require lower processing-reaction times. Consequently, they can drive safely with lower ASDs. Considering a PRT of 0.5 s, curves of less than 1600 m (Figure 8) would have to display reduced speed limits—assuming radar's cone of visibility and maximal VL are not limiting factors. A total of 86.4% of circular curves have a radius of less than 1600 m. There are only three circular curves that would have to display

reduced speed limits in the case of the human-driven case but not in the automated-driven case. Therefore, it can be said that even if only autonomous cars were considered, special measures would have to be taken to ensure truck platoons can be put on the roads without threatening road safety.

6 | CONCLUSION

It has been said that truck platooning would automatically mean an increase in road safety. But the contrary may occur if the infrastructure is not adapted for truck platoons. The effect of truck platooning on visibility is not a negligible effect. Most resources are being used in developing all the technology that surrounds the platooning system, but the effect of truck platoons on visibility still has to be deeply studied before running platoons.

Through the carried-out study, it has been seen that platoons could only be implemented on roads with a curve radius of at least 2500 to 2750 m—depending on the speed limit. That represents a low percentage of current freeways.

Regarding the adaptation of infrastructure, measures still have to be proposed. These measures will include speed limits reductions in order to ensure the required sight distance. Other solutions such as dynamic speed systems or the adaptation of curve geometric conditions must also be considered so speeds are kept as close as possible to current ones. This might include innovative solutions, as equipping truck platoons with dynamic lighting on the left part would allow overtaking the car's driver to be aware of an upcoming obstacle on the road. Vehicle-to-vehicle communication between all the vehicles on the road may also be required to allow truck platoons on roads. Thus, it would be possible to implement systems to warn of unexpected elements on the road. In this case, the conditioning parameter would not be visibility but communication range.

Regarding AVs, automated driving must be designed considering all of the safety issues involved. That could include the adaptation of speed limits—as stated before—but also measures related to the car's position. A combination of measures regarding automated driving may reduce the impact on road safety. The key question is: Would the increasing automation of the vehicle fleet be capable of compensating that visibility reduction?

A reduced gap between trucks will also have a clear effect on visibility. If truck platoons had larger gaps visibility reduction would not be important, but fuel consumption reduction would be much lower too. The threshold between fuel consumption reduction and visibility reduction is still to be found.



There are more parameters that influence safety and may be considered in further research. One of them is the duration of the visibility obstruction, which depends on both the gap length and the number of trucks forming the platoon. Dynamic simulations should be considered in the future to evaluate these parameters. Also, this model considers an infinite circular curve. Despite the high accuracy of the developed model, further development considering transition curves and finite curves should be done in order to simulate the real curve's visibility. Vertical alignment should also be included in the future to this model, as overlapping could both increase or decrease the estimated ASD. Other particular elements that may affect visibility, such as construction components or operating speeds, might also be included in further extensions of this model. In the case that truck platooning was also allowed on other roads, such as rural roads, the model might be adapted to simulate passing vehicles' visibility in two-lane two-way roads. Additionally, future extensions of this research may benefit from the use of other computational techniques such as machine learning. These would provide the necessary support to carry out new simulations considering additional parameters as stated before.

Last, there is an important lack of legislation. Having such an important effect on road safety, the inclusion of the effect on road design guidelines and standards should be considered. Limitations regarding speed limits or the increase of the highway curve's minimum radius might be within these considerations. New regulations to ensure safety conditions should also include what the minimum conditions of an existing highway should be if truck platooning was allowed.

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