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RISK ASSESSMENT IN RAMPS FOR HEAVY VEHICLES – A FRENCH STUDY

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ABSTRACT

This paper presents the results of a study dealing with the risk for heavy vehicles in ramps. Two approaches are used. On one hand, statistics are applied on several accidents databases to detect if ramps are more risky for heavy vehicles and to define a critical value for longitudinal slope. χ^2 test confirmed the risk in ramps and statistical analysis proved that a longitudinal slope superior to 3.2% represents a higher risk for heavy vehicles. On another hand, numerical simulations allow defining the speed profile in ramps for two types of heavy vehicles (tractor semi-trailer and 2-axles rigid body) and different loads. The simulations showed that heavy vehicles must drive more than 1000 m on ramps to reach their minimum speed. Moreover, when the slope is superior to 3.2%, tractor semi-trailer presents a strong decrease of their speed until 50 km/h. This situation represents a high risk of collision with other road users which drive at 80-90 km/h. Thus, both methods led to the determination of a risky configuration for heavy vehicles: ramps with a length superior to 1000 m and a slope superior to 3.2%. An application of this research work concerns design methods and guidelines. Indeed, this study provides threshold values than can be used by engineers to make mandatory specific planning like a lane for slow vehicles.

Keywords: heavy vehicles, ramps, longitudinal slope, speed profile, statistical analyses

1 Introduction

The French fleet of heavy vehicles is composed of almost 550 000 units (data in 2012) cumulating a total of 19.5 billion kilometres of travelled distance per year. Heavy vehicles represent 3.4% of the vehicles involved in accidents with injuries and 9.9% of fatal accidents (ONISR, 2012). The evolution of heavy vehicles accidents in France has shown a continuous decrease (5719 accidents in 2002 and 3148 in 2012), especially for tractors semi-trailers. This trend can be explained by the complementary actions of French safety policy and the development of active safety systems like ABS (Anti-lock Braking System) or ESP (Electronic Stability Program). Despite researches conducted in the past decade on accidents related to heavy vehicles, knowledge is still needed to better assess accidents in ramps. Indeed, as analysis of accidents data showed that rollover and jack-knifing in curves represent around 2/3 of accidents in Europe (Desfontaines, 2003) (UNIFI, 2003) and similar trends were found in the rest of the world (Cate et al., 2000) (Häkkänen et al., 2001) (Moonesinghe et al., 2003) (Tsaï et al., 2004), most research have mainly focussed on accidents occurring in curves. Thus, the case of ramps is less addressed.

An analysis of French accidents between 2005 and 2009 showed that 27% of accidents involving a heavy vehicle alone and 18% of accidents involving at least one heavy vehicle are observed on ramps (Cerezo et al., 2008).

Literature review showed that heavy vehicles accidents on American dual carriageways are more frequent in ramps (Agent et al., 2002). Most accidents occur by front-rear collisions, considering both corporal and material accidents, and are due to a speed difference of 40 to 50 km/h between the involved vehicles (cars moving faster than the slow heavy vehicle in front). Ramps with a longitudinal slope higher than 4% prove to be more risky on Swedish primary roads (Othman et al., 2007) whereas the threshold value is 2% in Italy (Caliendo et al., 2001) and in Washington State (Shankar et al., 1995). Moreover, Fu et al. (2011) found that not only the value of the longitudinal slope but also the length of the ramp have an impact on accident risk on primary roads in China.

This paper presents results of a research dealing with accident risk in ramps. It aims at improving knowledge about accidents in ramps and providing limit values for infrastructure characteristics to detect risky areas.

2 Research conducted

2.1 Collision risk on ramps

Study conducted on a French motorway between 1995 and 2001 highlighted the fact that one third of materials and corporals' heavy vehicles accidents occurred on ramps of 5 km in length, which represent only 2% of the motorway length (Cerezo et al., 2008). Average values of the longitudinal slope range between 4 and 5%. Accidents were mainly located after 1500 meters of ramp-up. Experiments were conducted to estimate the speed of heavy vehicles along a ramp and understand the causes of accidents. These experiments showed that after around 2500 meters of ramp-up, the speed of heavy vehicles was stabilized and the behavior of heavy vehicles can be split into two groups. In the first group, the vehicles were able to keep a constant speed on the ramp with an average value of 85 km/h. In the second group, vehicle's speeds decrease significantly and stabilize at around 55 km/h (Figure 1). Based on these results, safety experts concluded that accidents on ramps can be explained by a gap of speeds between the vehicles involved in the accident. They also underlined the fact that a longitudinal slope higher than 4% and a length of the ramp higher than 1500 m highly contribute to the speed reduction and as a consequence increase the collision risk.

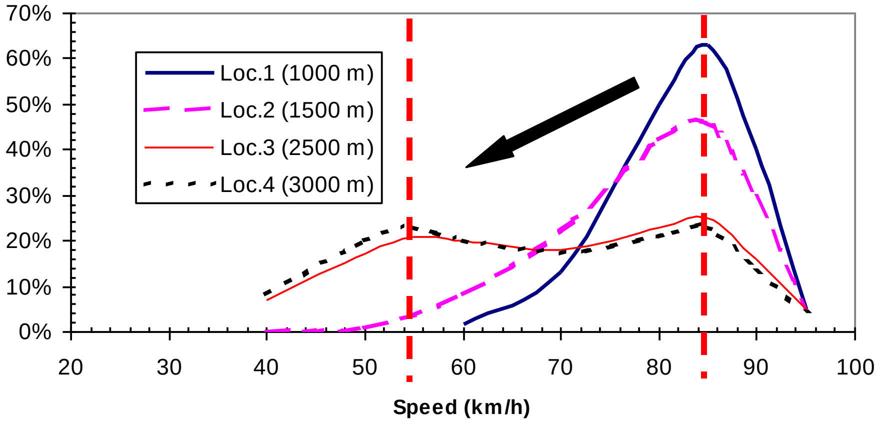

Figure 1 : Distribution of heavy vehicles' speed on different locations on the ramps (Cerezo et al., 2008)

To complete this previous study, statistical analysis was performed on accidents databases from two French regions (Rhône-Alpes and Auvergne). These two regions were chosen because they are representative of the traffic in France, with both transit (North-South) and local traffic, and geographical environments (plain, mountain, rural and urban). In a first step, accidents occurring between 2003 and 2008 were collected (**Figure 2**) and studied.

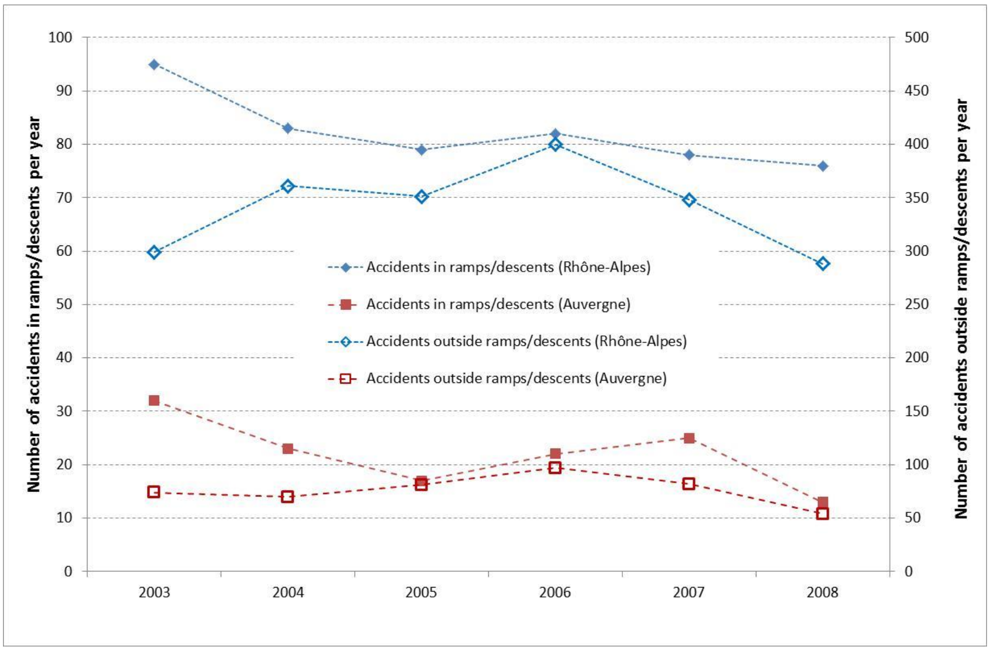

Figure 2 : Evolution of the annual number of accidents occurring in and outside ramps/descents

In Auvergne, the annual number of accidents in ramps/descents (resp. outside ramps/descents) ranges between 13 and 32 (resp. 54 and 97) whereas in Rhône-Alpes this number ranges between 76 and 95 (resp. 288 and 400). Firstly, the data are analyzed with Bayes method to assess if the year has an impact of the probability of accidents occurring in ramps/descents (**Figure 3**). The data are divided into six field classes (one per year). Two events are defined: H1 = {accidents occurring in ramps/descents} and H2 = {accidents occurring outside ramps/descents}. By using notations given in **Figure 3**, Bayes theorem says that:

$$P(H|E') = \sum_{E=1}^{N} P(H|E) * P(E|E') \tag{1}$$

$$P(Hi) = \sum_{j=1}^{6} P(Hi|Ej') \tag{2}$$

With i = 1 for accidents occuring in ramps/descents

i = 2 for accidents occurring outside ramps/descents.

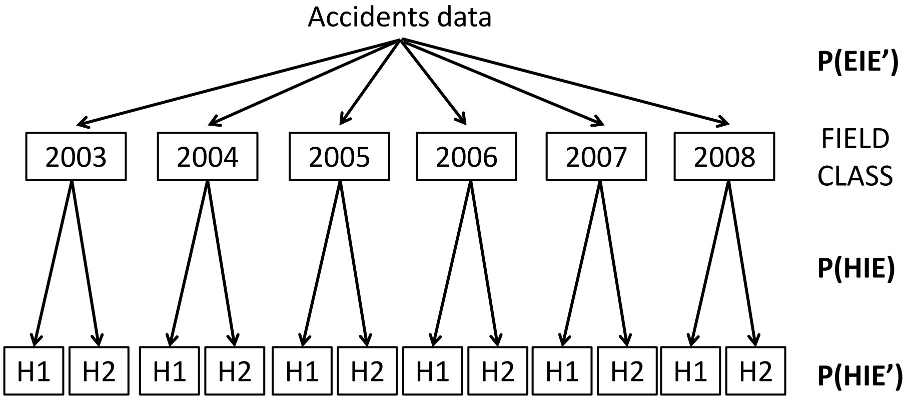

Figure 3 : Example of a map used to calculate probability of accidents with Bayes theorem

The results of the probability calculus are provided in Table 1.

Table 1 : Probabilities of accidents by using Bayes approach

Region	Event	2003	2004	2005	2006	2007	2008	P(Hi)
Rhône-Alpes	H1: Accidents in ramps/descents	0.04	0.03	0.03	0.03	0.03	0.03	0.19
	H2: Accidents outside ramps/descents	0.12	0.14	0.14	0.16	0.14	0.11	0.81
Auvergne	H1: Accidents in ramps/descents	0.05	0.04	0.03	0.04	0.04	0.02	0.22
	H2: Accidents outside ramps/descents	0.13	0.12	0.14	0.16	0.14	0.09	0.78

Table 1 shows that probabilities of accidents are very close from one year to another in both studied regions.

Then, traffic data are collected by road managers with vehicles counting stations located in various places on the road network (SIREDO system). Nevertheless, only average daily traffic values obtained by aggregating the whole six years traffic data on the different road sections were provided to perform this study. Thus, the hourly variance of daily traffic and the weekly variance of traffic volume cannot be introduced as a parameter of study. That is the reason why the analysis were based on simple crash rates.

In a second step, a χ^2-test was used to compare accident risk on and outside ramps/descents for different types of heavy vehicles. Thus, two configurations are considered: accidents occurring on ramps/descents and accidents occurring outside ramps/descents. As we wanted to assess the sensitivity of vehicles types to road geometry, we merged the six years accidents data and separated them in six classes of vehicles for the analysis (table 2).

Table 2 : Classes of heavy vehicles used in statistical analysis

Classes
HGV < 7,5t
HGV > 7,5t
HGV > 3,5t + trailer
Tractor
Tractor + semi-trailer
Unknown

To apply this statistical test, coefficients c_{ij} need to be calculated. These coefficients represent the expected numbers of accidents for class (i) of heavy vehicles and in configuration j during 6 years (2003 – 2008). Coefficients c_{ij} are defined as:

$$c_{ij} = \frac{m_i n_j}{n} \qquad (3)$$

With m$_i$: number of accidents occurring during six years for class (i) of vehicles

n$_j$: number of accidents occurring in a configuration (j) (j = 1 on ramps and j = 2 oustide the ramps)

n: number of accidents occurring during 6 years (reference period commonly adopted for safety studies is superior to 5 years) for both configurations in and outside ramps.

Then, the χ^2-value is determined and compared to a critical value. χ^2 is defined as:

$$\chi^2 = \sum \frac{\left(a_{ij} - C_{ij}\right)^2}{C_{ij}} \qquad (4)$$

With i: ranging from 1 to 6 (class of vehicles)

j: ranging from 1 to 2 (configuration)

a$_{ij}$: number of accidents which really occurred during six years in configuration (i) for the class of vehicles (j).

The critical value for the χ^2 test is 20.55 considering a 5-dof model (equal to “number of classes – 1”) and a confidence interval of 99% (Cochran, 1954).

Table 3 : χ^2-values for accidents in ramps/descents (2003 – 2008)

Region	Class	Accidents in ramps/descents	Accidents outside ramps/descents	Total (mi)	**Ci1**	**Ci2**	**χ²-value**
Rhône-Alpes	HGV < 7,5t	39	192	231	44,8	186,2	33,4
	HGV > 7,5t	155	706	861	167,1	693,9	
	HGV > 3,5t + trailer	105	457	562	109,1	452,9	
	Tractor	2	38	40	7,8	32,2	
	Tractor + semi-trailer	178	644	822	159,5	662,5	
	Unknown	14	10	24	4,7	19,3	
Auvergne	HGV < 7,5t	6	41	47	9,1	37,9	175,8
	HGV > 7,5t	32	187	219	42,5	176,5	
	HGV > 3,5t + trailer	29	70	99	19,2	79,8	
	Tractor	1	9	10	1,9	8,1	
	Tractor + semi-trailer	25	147	172	33,4	138,6	
	Unknown	39	0	39	7,6	31,4	

The χ^2-values calculated for the two regions are higher than the critical value which means that ramps/descents present a higher risk of accident than the rest of road infrastructure (i.e. outside ramps/descents) from a statistical point of view. It could be noticed that two values of

c_{ij} are lower than 5 (Table 3). As the percentage (compared with the population of c_{ij} values) is less than 20% (1 value over 12 values of coefficients c_{ij} for each region considered), the χ^2 can be still used (Cochran, 1954) (Armitage et al., 1971) (Agresti, 1990).

2.2 Effect of ramp slope

2.2.1 Methodology

Statistical comparisons of crash rates are used to go further in the analysis and assess the role of the slope of the ramp. The crash rate (CR) is defined as the number of crashes per 100 million vehicle-km of travel:

$$CR = \frac{N \times 10^8}{L \times T \times 365 \times n} \qquad (5)$$

Where N: number of crashes occurring during (n) years on a road section

L: length of the section (km)

T: average daily traffic on the section (veh/day)

n: number of years.

The crash rate determines the relative safety level of a road section (roadways, segments, or intersections). The most dangerous areas can be detected on a road network by considering the highest values of CR.

In this study, roads are divided into homogeneous sections based on the road characteristics and classes are defined (Conche et al., 2010). First of all, the influence of tolls and exit-way is not considered as former studies showed that these particular points of the itinerary induce a change in drivers’ behavior. A distance of 100 m is generally admitted as sufficient to hide their effect. All data included in an area of 100 m before and after a toll or an exit-way are excluded from the analyses. Then, the road network is divided into homogeneous sections by considering the existence of emergency lanes, the radius of curvature and the longitudinal slope. The split between straight line and curve is realized by taking a radius of curvature higher than 2000 m as a limit. Definition of the classes is detailed in section 2.2.3. **Figure 4** describes the steps to split the itineraries into homogenous sections.

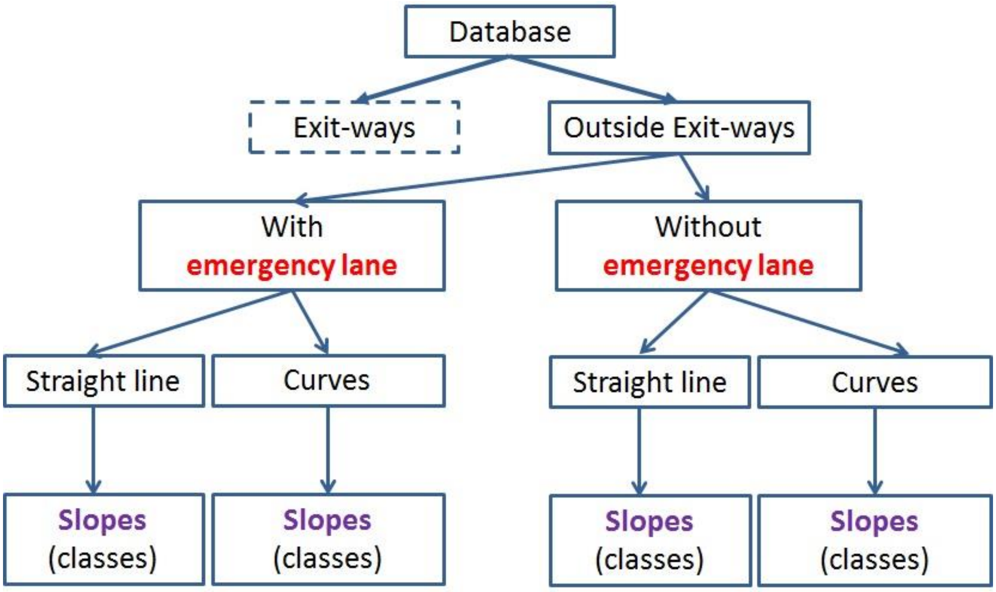

Figure 4 : Algorithm to split the database in homogeneous sections

Crash rates are then calculated by adding all accident data obtained in a given class. Statistical tests allow a comparison between the crash rates and see if one – or more – class of road characteristics represents a significant risk for heavy vehicles. A level of confidence of 95% is used to compare the crash rates.

2.2.2 Database

More than 10 000 accidents were collected between 2003 and 2010 on 1000 km of France highways network. They include both injury and damage-only accidents. The following geometrical characteristics are also collected: number of lanes, radius of curvature, longitudinal slope, presence of null cross fall, absence of emergency lane, zones with poor visibility, presence of climbing lanes, interchanges (Cerezo et al., 2014).

A brief overview of the database characteristics shows that 68% of the roads are dual carriageways and 32% present three lanes. Only 1% of the roads have no hard shoulder. More than 80% of the sections are on flat areas (Figure 5). The flat areas correspond to sections with a longitudinal slope lower than 2%. Finally, 19% of the lengths of radius are lower than 1000 m which is consistent with highways general characteristics.

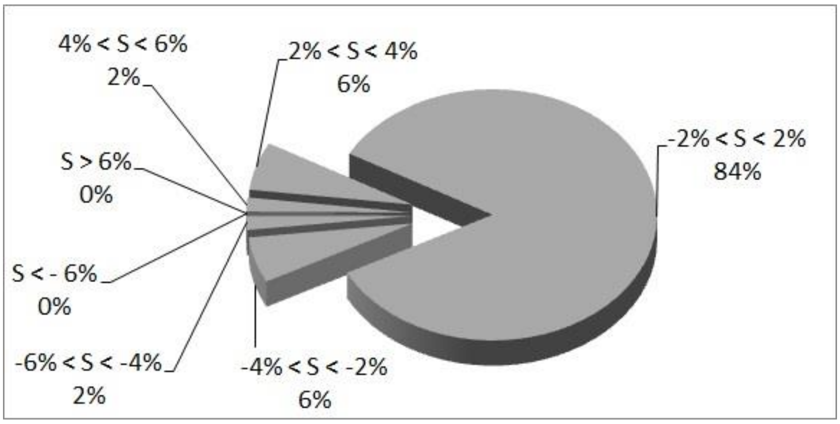

Figure 5 : Percentage of length of sections with various longitudinal slopes

For traffic data, average daily traffic data “T” calculated on the reference period were provided on a separate database by road manager networks for the various sections. They were calculated for each circulation flow.

2.2.3 Sampling method

As explained in section 2.2.1, the road network must be divided into homogeneous sections for the validation process. These sections are based on the definition of classes for the longitudinal slopes. The longitudinal slope is counted positive in ramps and negative in descents. The limits of the slope ranges are defined by considering two criterions. On the one hand, as the accuracy of measurements of the longitudinal slope is 0.5%, the width of the interval defining a class must be at least higher than 1%. On the other hand, this width must be as reduced as possible to make accurate analysis but each interval must contain enough data to allow consistent statistical tests. Thus, a width of 2% is considered (Table 4).

Table 4 : Definition of the initial classes of slope (Cerezo et al., 2014)

Slope in absolute value (%)	Sense
$S \leq 2$	Flat area
$2 < S \leq 4$	Descent
	Ramp
$4 < S \leq 6$	Descent
	Ramp

6 < S	Descent
	Ramp

2.2.4 *Results*

First, crashes rates for the different classes of slopes are calculated with a confidence interval of 95%. The aim is to estimate if one class of slopes presents a higher risk of accidents compared with the other. The reference class is defined as the class with slopes ranging from -2% to 2%. Accident rates are normalized on the graphics by dividing their values by the accidents rates on the reference section (i.e. flat area). We can consider that the level of risk is significantly higher for one class when the confidence intervals are separated. Thus, ramps with a slope higher than 4% are more dangerous for heavy vehicles (Figure 6).

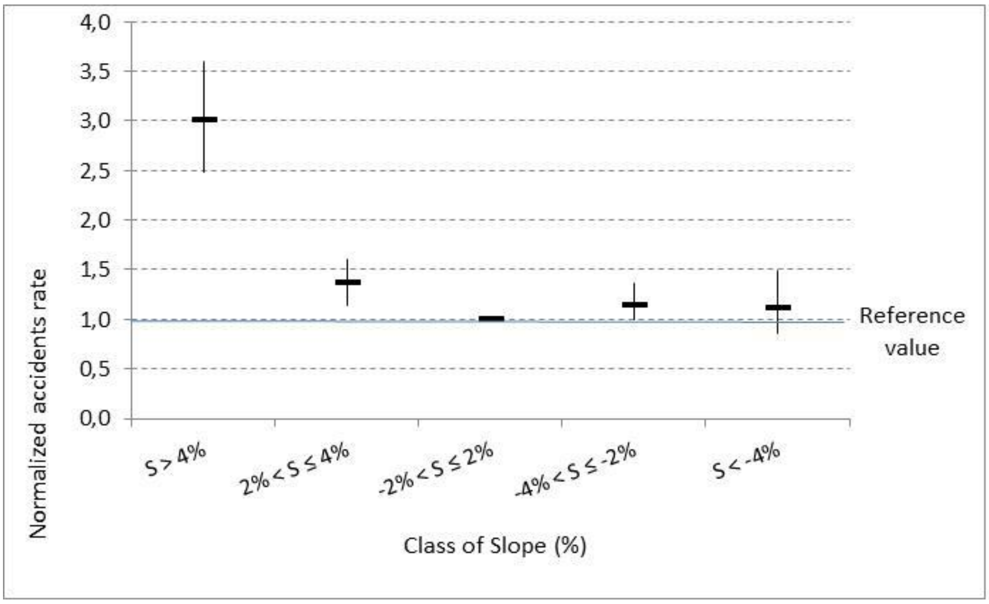

Figure 6 : Comparison of the normalized accidents rates obtained with the initial classes of slope (in %) with a level of confidence of 95%

In a second step, an attempt was made to change the limit values of the classes and refine this value of 4%. It aims at improving the accuracy of the critical value. New definition of classes is presented in Table 5.

Table 5 : Definition of the new classes of slope (Cerezo et al., 2014)

Slope in absolute value (%)	Sense
d ≤ 1.2	Flat area

1.2 < d ≤ 3.2	Descent
	Ramp
3.2 < d ≤ 4.5	Descent
	Ramp
4.5 < d	Descent
	Ramp

The whole accidents occurring on the same class of parameters are merged in view of determining accident rates for each class of characteristics. Moreover, the reference class is the one with a slope ranging between -1.2% and 1.2%, which is considered as a flat area. Figure 7 compares the normalized accident rates calculated for each new class of longitudinal slope with a level of confidence of 95%. Two classes present separate confidence intervals with the reference class, which means that the accidents rates are significantly different from a statistical point of view. Thus, ramps (resp. descent) with a slope higher than 3.2% (resp. -3.2%) present higher risk of accidents for heavy vehicles. Moreover, the risk on ramps with a slope higher than 3.2% is 2.5 times higher than the risk on flat area.

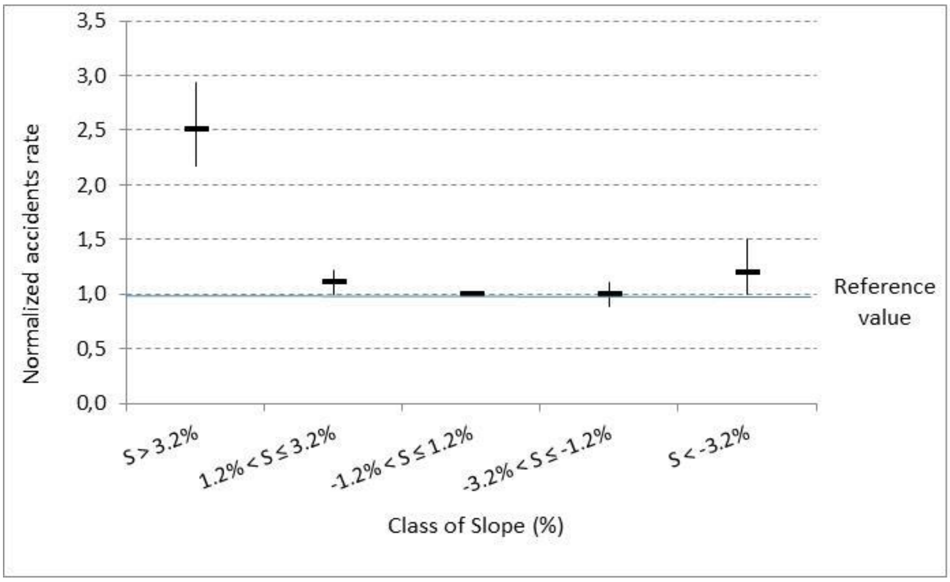

Figure 7 : Comparison of the normalized accidents rates obtained with the new classes of slope (in %) with a level of confidence of 95%

Statistical analysis confirmed the risk presented by ramps and descents with a longitudinal slope higher than 3.2%. These critical values can thus be used in road safety tool to detect risky areas.

2.3 Refined analysis by modeling

Numerical simulations are then used to confirm the results obtained by statistical methods. Heavy vehicles' models are used to estimate speed profiles along a ramp and determine the maximum speed difference between heavy vehicles (considered as slow vehicles) and passenger cars which are able to maintain their speed in ramps. Two parameters are considered for the simulations: the longitudinal slope of the ramp and the load of the heavy vehicles.

2.3.1 Vehicle model

Simulations are performed by means of a commercial software called PROSPER (PROgram of SPEcification and Research components), developed in the nineties. The calculation algorithm is based on a coupled and non-linear system with more than 100 degrees of freedom and hundreds variables. The input parameters are geometrical characteristics of the road (longitudinal slope, transversal profile, etc.), surface characteristics (skid resistance, unevenness) and heavy vehicles characteristics (type, load, etc.). The output parameters are the dynamic state of heavy vehicles (speed, accelerations, etc.).

Ramps are modeled by straight lines with a constant slope ranging between 3 and 7%. The crossfall is equal to 2.5% as specified in French design guidelines.

A 5-axles articulated vehicle – tractor semi-trailer - and a 2-axles rigid vehicle are considered. These two categories of vehicles represent more than 60% of trucks on the

French roads network. Tyres are modelled by a Pacejka's model (Pacejka, 2002). The weight of the tractor semi-trailer ranges from 15000 kg to 38000 kg, depending on the load in the trailer, and the weight of the 2-axles rigid vehicle ranges from 13000 kg to 19000 kg. The speed is 90 km/h at the bottom of the ramp, which is the maximum legal speed in France for heavy vehicles. The driver uses the optimal gear in view of minimizing the stress on the engine. The parameters of the engine are chosen to be representative of heavy vehicles (more than ten years old), which are less powerful than new trucks and more sensitive to longitudinal profile variations. The simulations aim at determining the final speed on the top of the ramp depending on the load of HGV and the slope.

2.3.2 Results of numerical simulations

Figure 8 and Figure 9 present the speed of two types of heavy vehicles with two loads for four values of the longitudinal slope. Two behaviours can be observed depending on the category of vehicles. For a tractor semi-trailer, a steady decrease of the speed is observed until reaching a minimum value, whatever the load. For an empty two-axles rigid heavy vehicle, a steady decrease of the speed is first observed. Then, speed variations appear due to a driver's manoeuvre to keep the vehicle speed as high as possible by changing the gear ratio.

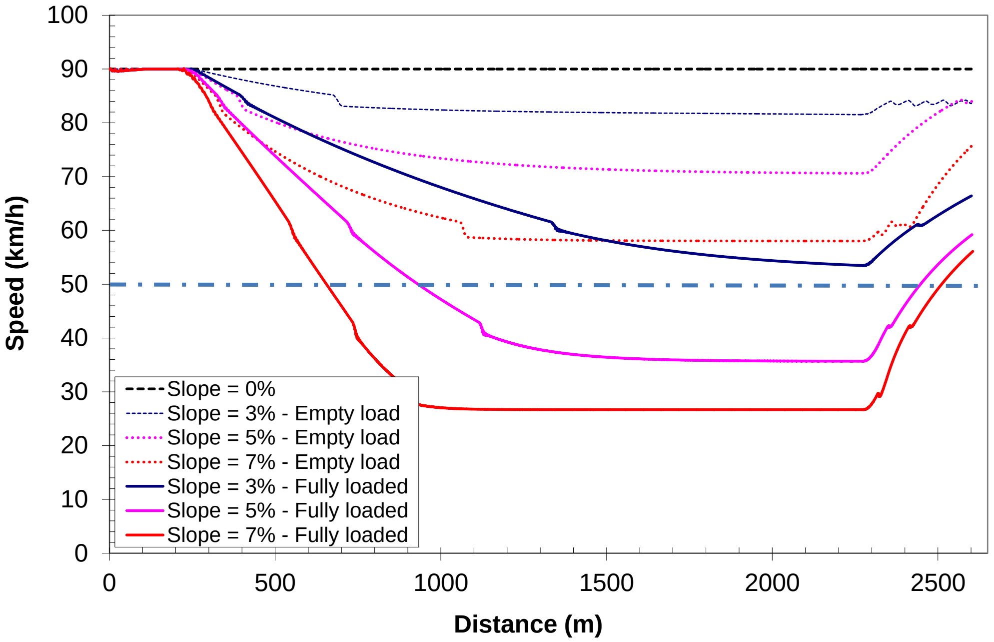

Figure 8 : 5-axels articulated heavy vehicles' speed on ramps with three values of longitudinal slopes and two loads

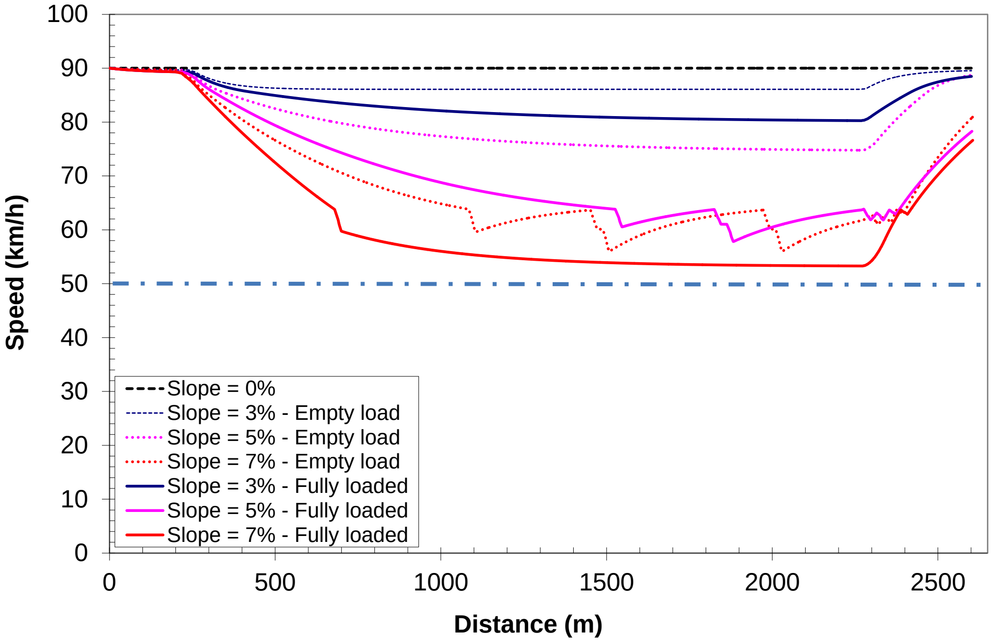

Figure 9 : 2-axels rigid heavy vehicles' speed on ramps with three values of longitudinal slopes and two loads

Considering regulations on highway, a minimum speed of 50 km/h is allowed. This situation happens after 700 m (resp. 900 m) of ramps for fully loaded tractor semi-trailer when the longitudinal slope is 7% (resp. 5%). Nevertheless, in some other cases (fully loaded 2-axles rigid vehicles on slope superior to 5%, fully loaded 5-axles articulated vehicle on slope of 3%), the minimum speed is also around 55 km/h, which is close to the critical value.

2.3.3 Definition of risky configuration for heavy vehicles

Figure 10 represents the minimum speed in ramps as a function of the longitudinal slope for the two types of heavy vehicles and two different loads. Numerical simulations show that empty heavy vehicles never reach the minimum value of 50 km/h. Then, the 2 axles-rigid body fully loaded has a minimum speed rather close to 50 km/h when the longitudinal slope is equal to 7%. Moreover, this situation occurs in the case of fully loaded tractor semi-trailer after 700-900 m of ramps and a longitudinal slope superior to 3.2%.

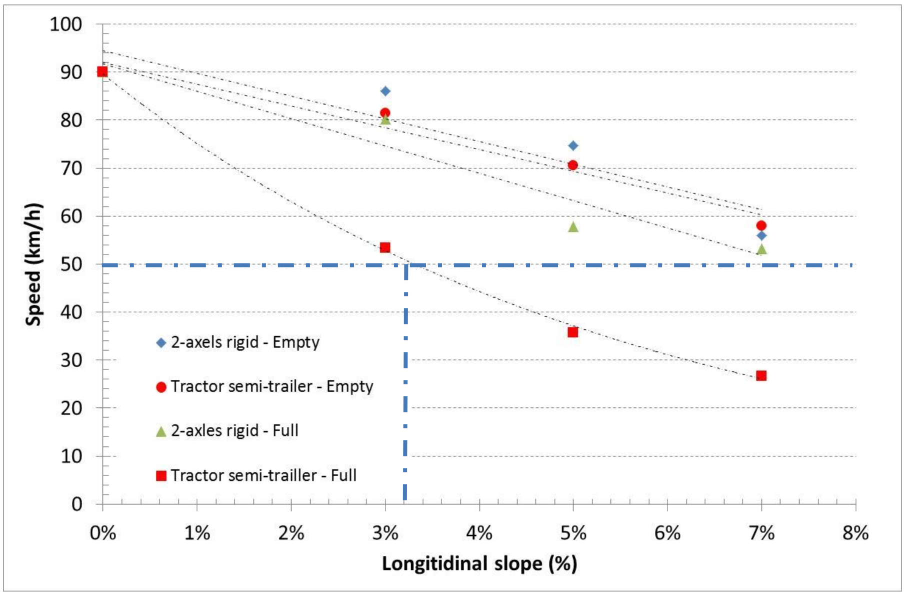

Figure 10 : Minimum speed in the ramps for various loads and longitudinal slopes

Thus, regarding the minimum speed reached in the ramp in the different configurations, a value of 3.2% for the longitudinal slope can be considered as a threshold. This conclusion confirms results provided by statistical analysis.

3 Conclusion

This paper aims at assessing the risk in ramps for heavy vehicles. Two approaches are used and their results are compared. On one hand, statistical analyses are conducted in view of defining if ramps represent a risk for heavy vehicles. The tests are done on several databases covering more than 1000 km of road network. A χ^2-test concludes that ramps/descents are significantly more risky for heavy vehicles than other places. Additional tests show that a critical value of 3.2% can be considered for longitudinal slope.

On another hand, numerical simulations are used to refine the results obtained by statistical approach. Two types of heavy vehicles are considered: 5-axles articulated heavy vehicles and 2-axles rigid heavy vehicles. A two steps methodology was applied with numerical simulations work to analyze the speed profile of heavy vehicles for various longitudinal slopes (0 to 7%) and define critical values for the road parameters. Results confirmed that a longitudinal slope of 3.2% entails a decrease of speed of fully loaded tractor semi-trailer until 50 km/h. At this speed, the risk of collision drastically increases with other road users driving at 80-90 km/h. Moreover, the simulations show that the ramp must have a length longer than 1000 m to allow heavy vehicles reaching the minimum speed.

Thus, both methods used in this study led to the conclusion that ramps with a longitudinal slope higher than 3.2% and a length longer than 1000 m is risky for heavy vehicles. This configuration can be used in diagnosis tool in the future to detect risky situation. Another application of this research work concerns design methods and guidelines. Indeed, this study provides threshold values than can be applied in road planning. Road engineers can be advised to avoid such configuration in the design phase. When it is not possible considering the location of the road (mountain, hills), guidelines can make mandatory the building of a specific lane for slow vehicles in ramps. The main result of this work is the fact that it provides a quantitative criterion that can be directly included in guidelines. Further analysis should be performed by introducing Bayes method and considering weekly variance of daily traffic and hourly variance of traffic volume. However, this approach requires an access to traffic raw data which is rather difficult to obtain especially on toll highways where this type of data is very sensitive considering economical stakes.

4 Acknowledgements

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