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1 **RISK ASSESSMENT IN RAMPS FOR HEAVY VEHICLES – A FRENCH STUDY**

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7
8 **ABSTRACT**

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

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

26 **1 Introduction**

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

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

44 Literature review showed that heavy vehicles accidents on American dual carriageways are
45 more frequent in ramps (Agent et al., 2002). Most accidents occur by front-rear collisions,
46 considering both corporal and material accidents, and are due to a speed difference of 40 to
47 50 km/h between the involved vehicles (cars moving faster than the slow heavy vehicle in
48 front). Ramps with a longitudinal slope higher than 4% prove to be more risky on Swedish
49 primary roads (Othman et al., 2007) whereas the threshold value is 2% in Italy (Caliendo et
50 al., 2001) and in Washington State (Shankar et al., 1995). Moreover, Fu et al. (2011) found

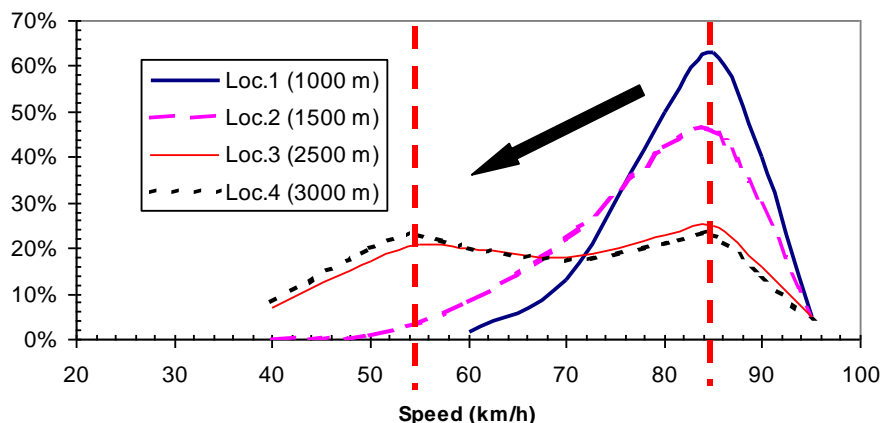
51 that not only the value of the longitudinal slope but also the length of the ramp have an
52 impact on accident risk on primary roads in China.

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

56 **2 Research conducted**

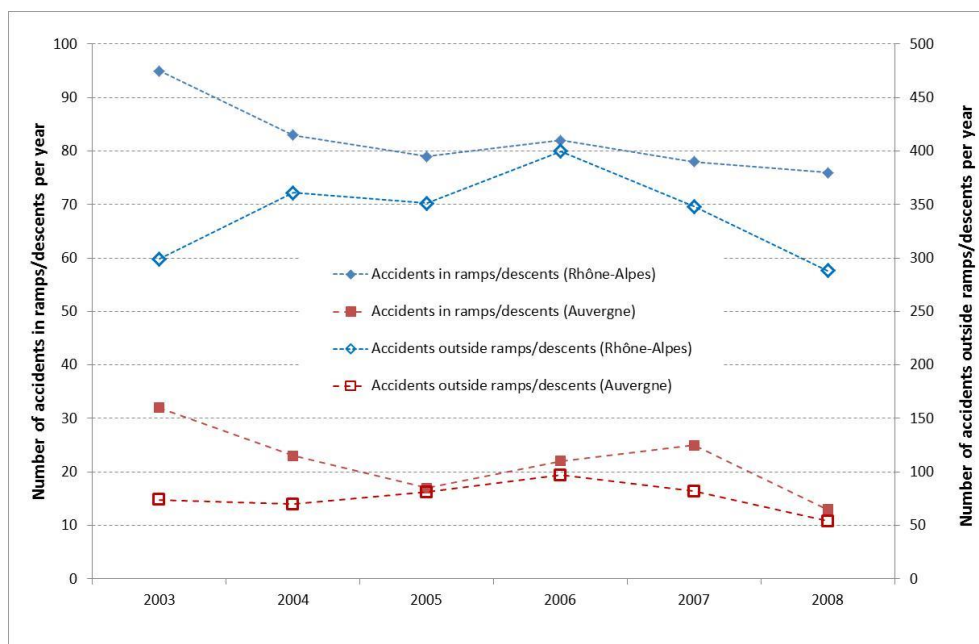
57 **2.1 Collision risk on ramps**

58 Study conducted on a French motorway between 1995 and 2001 highlighted the fact that one
59 third of materials and corporals' heavy vehicles accidents occurred on ramps of 5 km in
60 length, which represent only 2% of the motorway length (Cerezo et al., 2008). Average
61 values of the longitudinal slope range between 4 and 5%. Accidents were mainly located after
62 1500 meters of ramp-up. Experiments were conducted to estimate the speed of heavy vehicles
63 along a ramp and understand the causes of accidents. These experiments showed that after
64 around 2500 meters of ramp-up, the speed of heavy vehicles was stabilized and the behavior
65 of heavy vehicles can be split into two groups. In the first group, the vehicles were able to
66 keep a constant speed on the ramp with an average value of 85 km/h. In the second group,
67 vehicle's speeds decrease significantly and stabilize at around 55 km/h (Figure 1). Based on
68 these results, safety experts concluded that accidents on ramps can be explained by a gap of
69 speeds between the vehicles involved in the accident. They also underlined the fact that a
70 longitudinal slope higher than 4% and a length of the ramp higher than 1500 m highly
71 contribute to the speed reduction and as a consequence increase the collision risk.



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

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



79
 80 **Figure 2** : Evolution of the annual number of accidents occurring in and outside
 81 ramps/descents

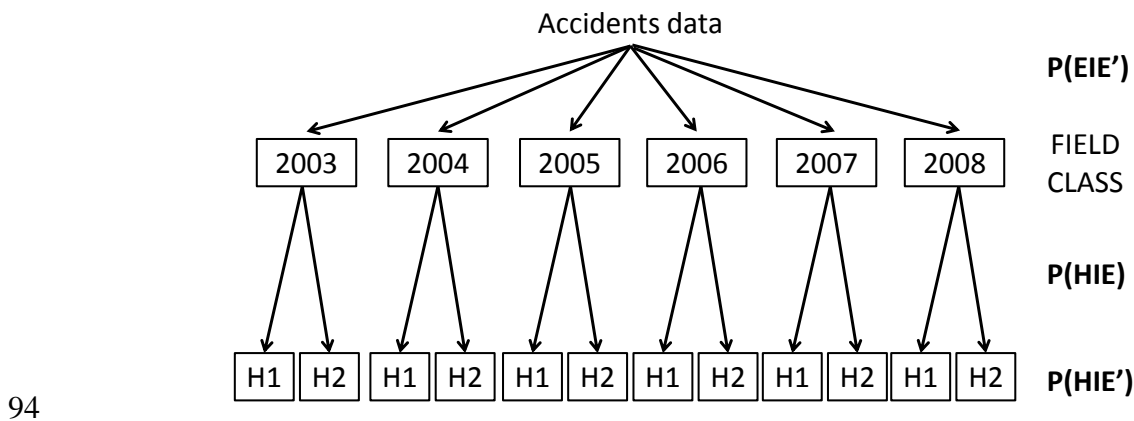
82 In Auvergne, the annual number of accidents in ramps/descents (resp. outside
 83 ramps/descents) ranges between 13 and 32 (resp. 54 and 97) whereas in Rhône-Alpes this
 84 number ranges between 76 and 95 (resp. 288 and 400). Firstly, the data are analyzed with
 85 Bayes method to assess if the year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

90
$$P(H|E') = \sum_{E=1}^N P(H|E) * P(E|E') \quad (1)$$

91
$$P(H_i) = \sum_{j=1}^6 P(H_i|E_j')$$
 (2)

92 With i = 1 for accidents occurring in ramps/descents

93 i = 2 for accidents occurring outside ramps/descents.



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

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

97 **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

98

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

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

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

112 **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

113

114 To apply this statistical test, coefficients c_{ij} need to be calculated. These coefficients represent
115 the expected numbers of accidents for class (i) of heavy vehicles and in configuration j during
116 6 years (2003 – 2008). Coefficients c_{ij} are defined as:

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

118 With m_i : number of accidents occurring during six years for class (i) of vehicles
 119 n_j : number of accidents occurring in a configuration (j) (j = 1 on ramps and j = 2
 120 outside the ramps)
 121 n: number of accidents occurring during 6 years (reference period commonly adopted
 122 for safety studies is superior to 5 years) for both configurations in and outside ramps.

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

$$\chi^2 = \sum \frac{(a_{ij} - c_{ij})^2}{c_{ij}} \quad (4)$$

125 With i: ranging from 1 to 6 (class of vehicles)
 126 j: ranging from 1 to 2 (configuration)
 127 a_{ij} : number of accidents which really occurred during six years in configuration (i) for
 128 the class of vehicles (j).

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

131 **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	χ^2 -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	

132
 133 The χ^2 -values calculated for the two regions are higher than the critical value which means
 134 that ramps/descents present a higher risk of accident than the rest of road infrastructure (i.e.
 135 outside ramps/descents) from a statistical point of view. It could be noticed that two values of

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

139 **2.2 Effect of ramp slope**

140 *2.2.1 Methodology*

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

$$144 \quad CR = \frac{N \times 10^8}{L \times T \times 365 \times n} \quad (5)$$

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

146 L: length of the section (km)

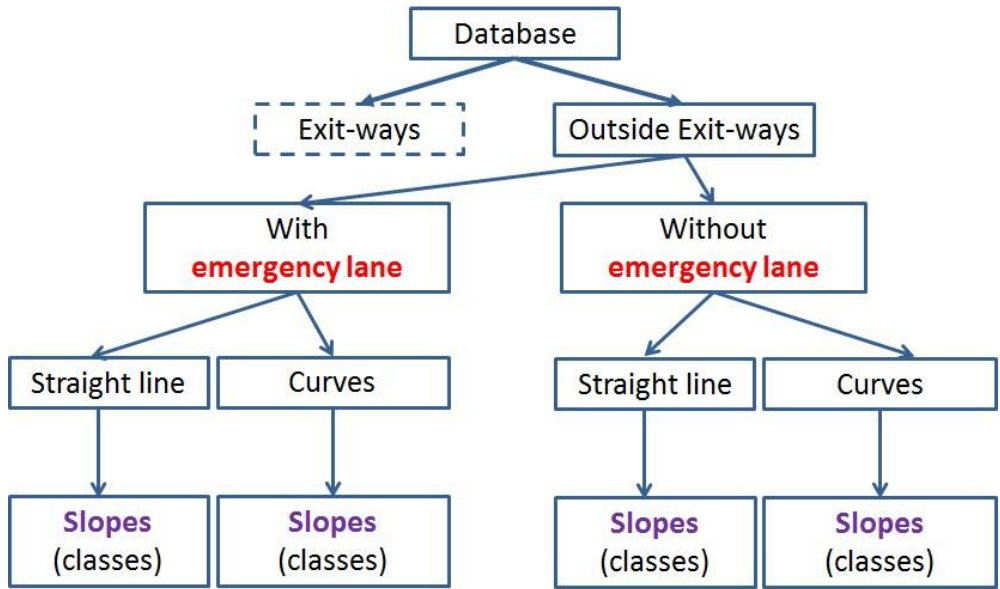
147 T: average daily traffic on the section (veh/day)

148 n: number of years.

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

152 In this study, roads are divided into homogeneous sections based on the road characteristics
153 and classes are defined (Conche et al., 2010). First of all, the influence of tolls and exit-way
154 is not considered as former studies showed that these particular points of the itinerary induce
155 a change in drivers' behavior. A distance of 100 m is generally admitted as sufficient to hide
156 their effect. All data included in an area of 100 m before and after a toll or an exit-way are
157 excluded from the analyses. Then, the road network is divided into homogeneous sections by
158 considering the existence of emergency lanes, the radius of curvature and the longitudinal
159 slope. The split between straight line and curve is realized by taking a radius of curvature

160 higher than 2000 m as a limit. Definition of the classes is detailed in section 2.2.3. **Figure 4**
 161 describes the steps to split the itineraries into homogenous sections.



162
 163 **Figure 4** : Algorithm to split the database in homogeneous sections

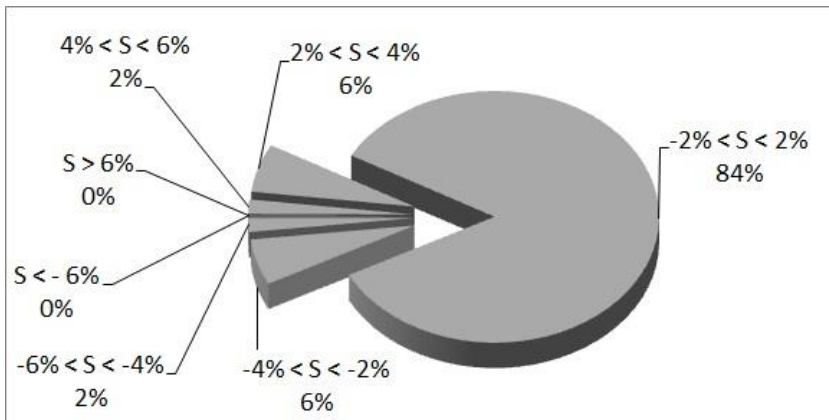
164 Crash rates are then calculated by adding all accident data obtained in a given class.
 165 Statistical tests allow a comparison between the crash rates and see if one – or more – class of
 166 road characteristics represents a significant risk for heavy vehicles. A level of confidence of
 167 95% is used to compare the crash rates.

168 *2.2.2 Database*

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

174 A brief overview of the database characteristics shows that 68% of the roads are dual
 175 carriageways and 32% present three lanes. Only 1% of the roads have no hard shoulder. More
 176 than 80% of the sections are on flat areas (Figure 5). The flat areas correspond to sections

177 with a longitudinal slope lower than 2%. Finally, 19% of the lengths of radius are lower than
 178 1000 m which is consistent with highways general characteristics.



179

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

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

184 *2.2.3 Sampling method*

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

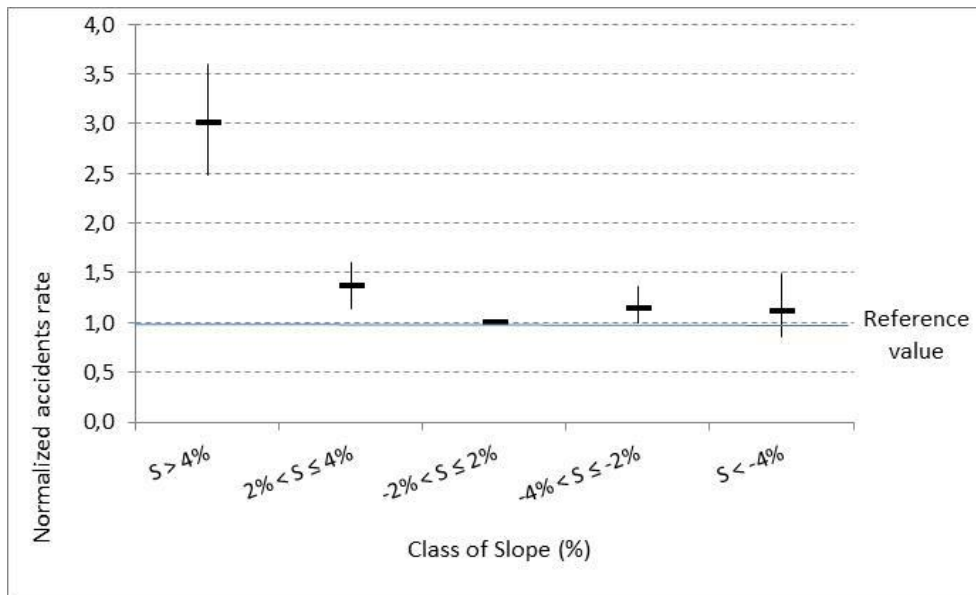
193 **Table 4 :** Definition of the initial classes of slope (Cerezo et al., 2014)

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

194 2.2.4 Results

195 First, crashes rates for the different classes of slopes are calculated with a confidence interval
 196 of 95%. The aim is to estimate if one class of slopes presents a higher risk of accidents
 197 compared with the other. The reference class is defined as the class with slopes ranging from
 198 -2% to 2%. Accident rates are normalized on the graphics by dividing their values by the
 199 accidents rates on the reference section (i.e. flat area). We can consider that the level of risk is
 200 significantly higher for one class when the confidence intervals are separated. Thus, ramps
 201 with a slope higher than 4% are more dangerous for heavy vehicles (Figure 6).



202

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

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

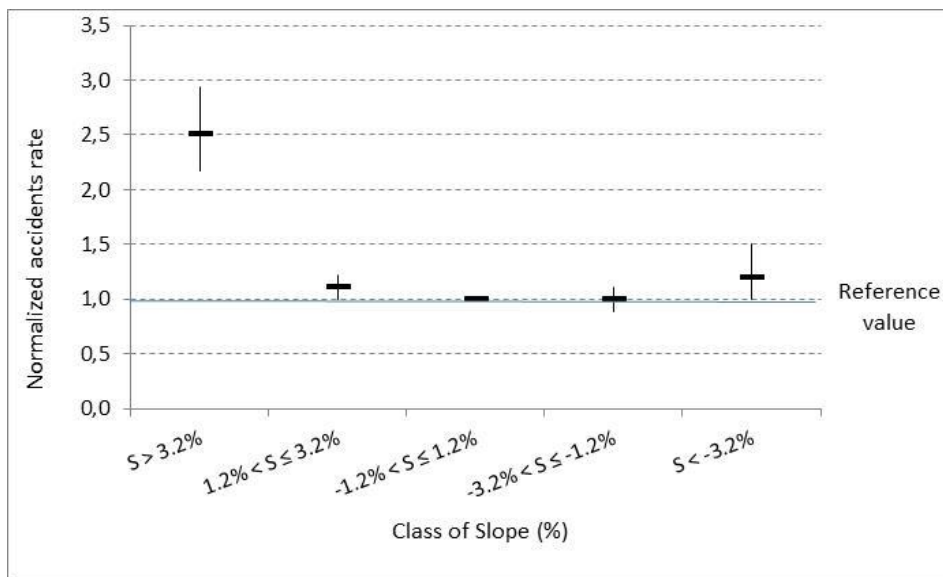
208 **Table 5 :** Definition of the new classes of slope (Cerezo et al., 2014)

Slope in absolute value (%)	Sense
$d \leq 1.2$	Flat area

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

209

210 The whole accidents occurring on the same class of parameters are merged in view of
 211 determining accident rates for each class of characteristics. Moreover, the reference class is
 212 the one with a slope ranging between -1.2% and 1.2%, which is considered as a flat area.
 213 Figure 7 compares the normalized accident rates calculated for each new class of longitudinal
 214 slope with a level of confidence of 95%. Two classes present separate confidence intervals
 215 with the reference class, which means that the accidents rates are significantly different from
 216 a statistical point of view. Thus, ramps (resp. descent) with a slope higher than 3.2% (resp. -
 217 3.2%) present higher risk of accidents for heavy vehicles. Moreover, the risk on ramps with a
 218 slope higher than 3.2% is 2.5 times higher than the risk on flat area.



219

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

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

225 **2.3 Refined analysis by modeling**

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

232 *2.3.1 Vehicle model*

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

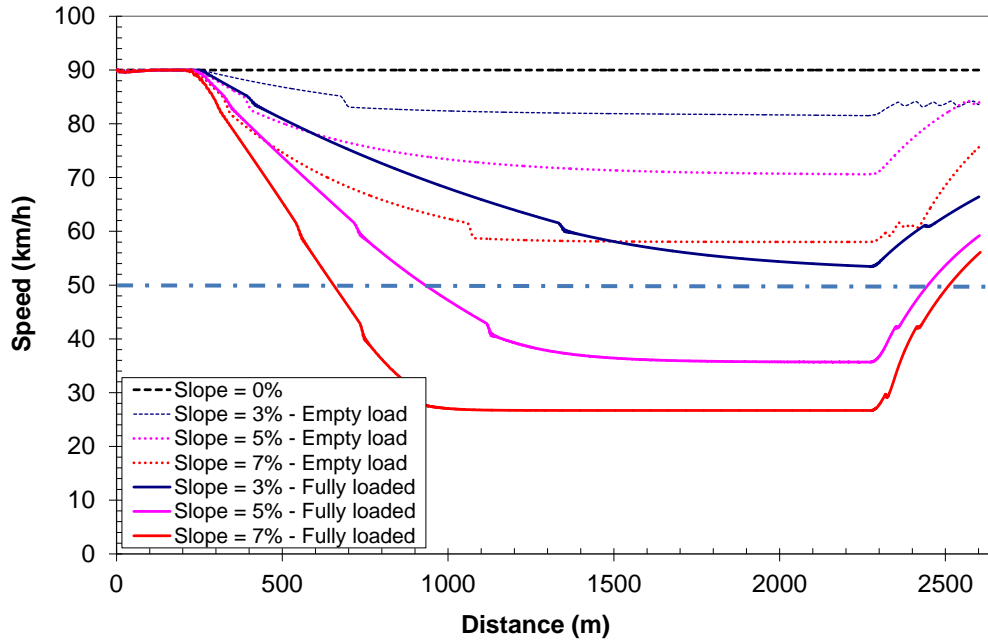
240 Ramps are modeled by straight lines with a constant slope ranging between 3 and 7%. The
241 crossfall is equal to 2.5% as specified in French design guidelines.

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

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

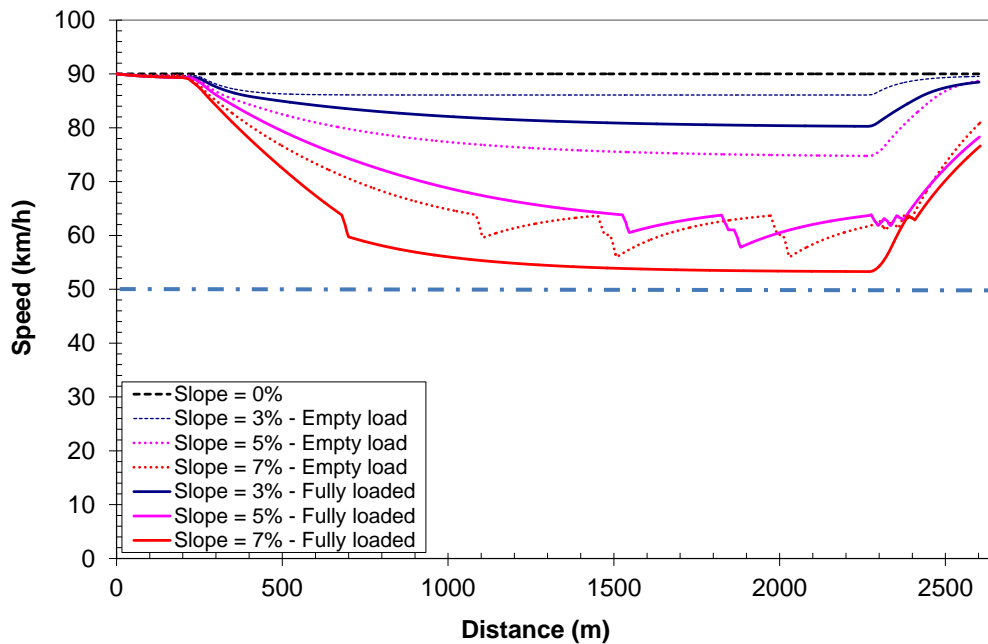
253 *2.3.2 Results of numerical simulations*

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



260

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



263

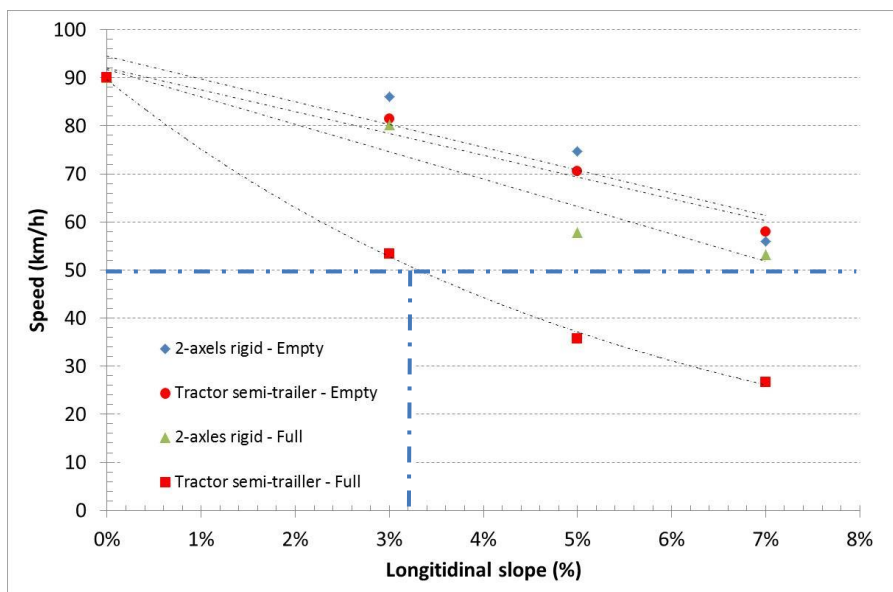
264 **Figure 9 :** 2-axels rigid heavy vehicles' speed on ramps with three values of longitudinal
 265 slopes and two loads

266 Considering regulations on highway, a minimum speed of 50 km/h is allowed. This situation
 267 happens after 700 m (resp. 900 m) of ramps for fully loaded tractor semi-trailer when the

268 longitudinal slope is 7% (resp. 5%). Nevertheless, in some other cases (fully loaded 2-axes
 269 rigid vehicles on slope superior to 5%, fully loaded 5-axes articulated vehicle on slope of
 270 3%), the minimum speed is also around 55 km/h, which is close to the critical value.

271 2.3.3 Definition of risky configuration for heavy vehicles

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



278

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

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

283 **3 Conclusion**

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

290 On another hand, numerical simulations are used to refine the results obtained by statistical
291 approach. Two types of heavy vehicles are considered: 5-axles articulated heavy vehicles and
292 2-axles rigid heavy vehicles. A two steps methodology was applied with numerical
293 simulations work to analyze the speed profile of heavy vehicles for various longitudinal
294 slopes (0 to 7%) and define critical values for the road parameters. Results confirmed that a
295 longitudinal slope of 3.2% entails a decrease of speed of fully loaded tractor semi-trailer until
296 50 km/h. At this speed, the risk of collision drastically increases with other road users driving
297 at 80-90 km/h. Moreover, the simulations show that the ramp must have a length longer than
298 1000 m to allow heavy vehicles reaching the minimum speed.

299 Thus, both methods used in this study led to the conclusion that ramps with a longitudinal
300 slope higher than 3.2% and a length longer than 1000 m is risky for heavy vehicles. This
301 configuration can be used in diagnosis tool in the future to detect risky situation. Another
302 application of this research work concerns design methods and guidelines. Indeed, this study
303 provides threshold values than can be applied in road planning. Road engineers can be
304 advised to avoid such configuration in the design phase. When it is not possible considering
305 the location of the road (mountain, hills), guidelines can make mandatory the building of a
306 specific lane for slow vehicles in ramps. The main result of this work is the fact that it
307 provides a quantitative criterion that can be directly included in guidelines. Further analysis

308 should be performed by introducing Bayes method and considering weekly variance of daily
309 traffic and hourly variance of traffic volume. However, this approach requires an access to
310 traffic raw data which is rather difficult to obtain especially on toll highways where this type
311 of data is very sensitive considering economical stakes.

312 **4 Acknowledgements**

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