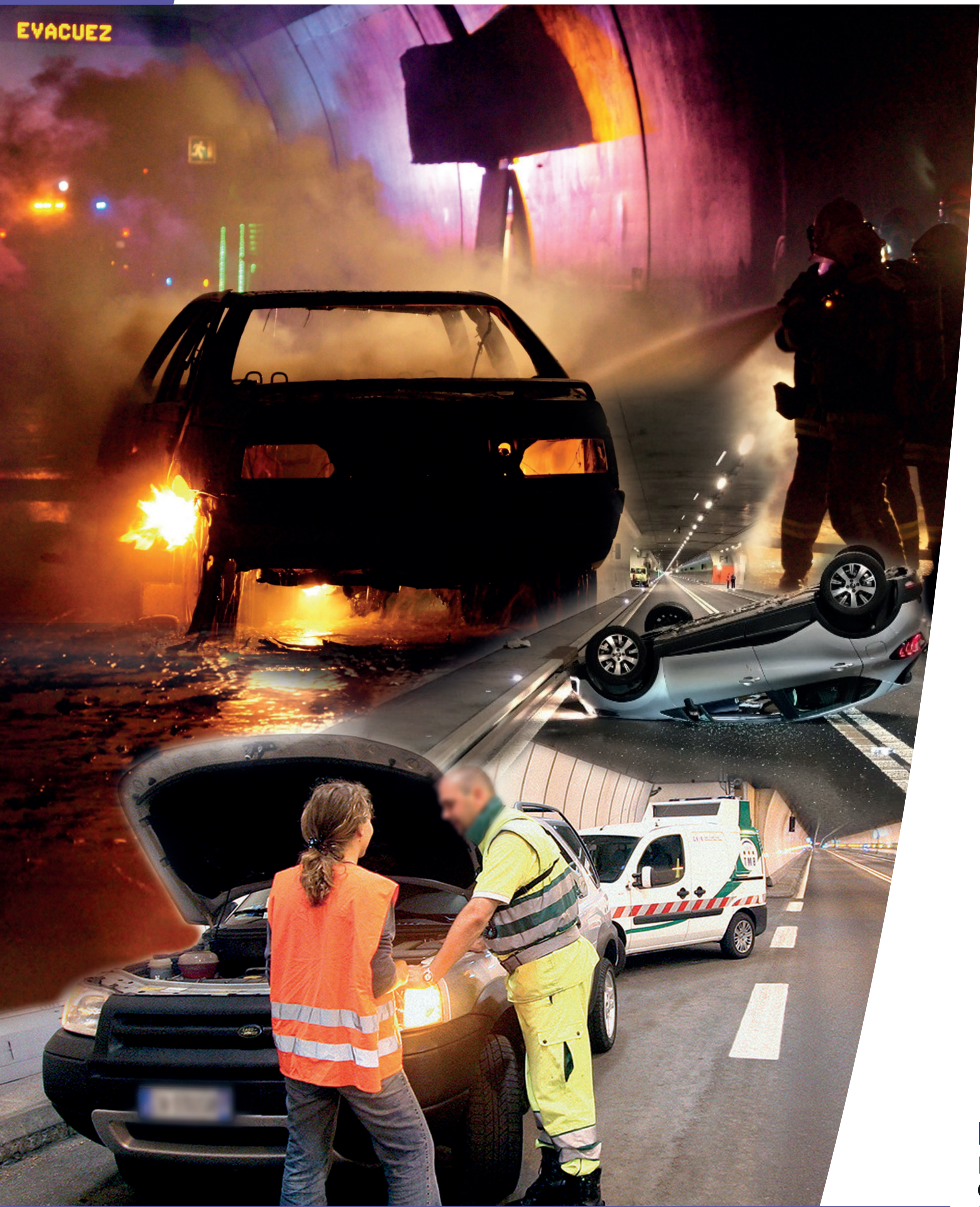
Information documents

BREAKDOWNS, ACCIDENTS AND FIRES IN ROAD TUNNELS

Statistics



February 2022

Centre d'Études des Tunnels (Centre for Tunnel Studies)

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Statistics

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1 INTRODUCTION

This information document is the result of CETU-led statistical work on breakdowns, accidents and fires in road tunnels. This introduction outlines the origins and goals of this work, details the studies carried out by CETU and its partners, and explains the scope of the results. The remainder of the document provides a summary of the results for each type of incident: breakdowns, accidents and fires.

1.1 CONTEXT AND GOALS

National statistics on breakdowns, accidents and fires in road tunnels are presented and analysed regularly throughout this document.

These statistics give owners and operators a general overview of the situation, which can help them consider their own structures and support their own analyses. They also serve as a key entry point for risk assessments, which form part of tunnel safety documentation, as well as providing input for wider research on tunnel safety.

These statistics are presented as incident occurrence rates per vehicle and per kilometre travelled.

In conducting this research, CETU intended to update existing statistics, which were derived from its 1998 publication “Breakdowns, accidents and fires in French road tunnels”.

The aims of this approach were twofold.

The first aim was to make the occurrence rates more representative, since some of the old rates were based on short and outdated datasets and/or on a small number of structures. The newly established rates are therefore more accurate and more representative of all tunnels (the old rates are given in the Appendix, in section 6.1, for information purposes).

The second aim was to more reliably identify the parameters influencing these rates. The “simple” methods used in the past meant that it was only possible to study the influence of a single parameter on an occurrence rate. Although such methods were easy to use and convenient in terms of presentation, they failed to capture potential dependencies between parameters. By using in-depth methods for this study, it was possible to identify those parameters that influenced the occurrence rate independently of the others and, where feasible, to quantify this influence.

1.2 STUDIES CARRIED OUT

The preparatory work for this study revealed gaps in available statistics on breakdowns, accidents and fires in road tunnels. As part of this preparatory work, which aimed to update these statistics, CETU clarified the scope, constraints and goals of the data collection and analysis work, the occurrence rates that would be calculated, and the expected approach to the influencing parameters in terms of simple and in-depth statistical methods.

Consulting firm BG Ingénieurs Conseils was then commissioned to carry out a study, with support from the École Polytechnique Fédérale de Lausanne (EPFL). The initial approach involved using simple regression analyses, i.e. analyses involving one parameter at a time. The in-depth method was then used to determine the influencing parameters: multiple regressions involving several parameters at once were carried out to determine which had an influence independently of the others.

CETU analysed this study and its findings then conducted further investigations in order to put forward hypotheses explaining the influence of certain parameters. Simple and multiple regressions were then carried out in order to test these hypotheses, and the parameters influencing personal injury accidents were investigated further. More than a dozen influencing parameters were considered in total.

From all of these studies, only the most significant results – and those supported by statistically representative samples – were retained. For instance, it was not possible to determine year-on-year changes in the rate across the period covered by the data, in part because available incident data was piecemeal prior to the installation of automatic incident detection systems.

Further information about the data collection method, the rate calculations and the multiple regression analyses is provided in the Appendix, in sections 7, 8.1 and 8.2 respectively.

1.3 DÉFINITIONS

This section contains definitions of the key terms and concepts used throughout this document.

Breakdowns

The breakdowns considered in this document concern vehicles. It does not address breakdowns affecting tunnel equipment. A breakdown is a mechanical or electronic malfunction that causes the vehicle to come to a stop. Where a distinction could be made, voluntary stops were not treated as breakdowns in the dataset. Incidents in which a vehicle stopped for less than 5 minutes and restarted without third-party assistance or without the driver having to exit the vehicle were also not treated as breakdowns.

Accidents

A road traffic accident is a collision between a vehicle (car, powered two-wheeler, bicycle, etc.) and another vehicle, or between a vehicle and an obstacle or a person, that causes physical damage and/or injures to one or more people. The damage can be sustained by the vehicle(s) involved, by part of the road or structure (roadway, signs, protective barriers, etc.), or by any other object in the surrounding environment (building, street furniture, tree, etc.). In the remainder of this document, road traffic accidents are referred to simply as “accidents”.

Fatalities and injuries

On 1 January 2005, France adopted the internationally accepted definition of a “fatality” as someone who dies within 30 days after an accident. This change was made in order to make its accident statistics comparable with those of its European neighbours. Up to and including the end of 2004, the French definition of “fatality” meant someone who died at the scene or within six days after an accident. Following the change of definition, the term now refers to someone who dies at the scene or within 30 days.

The concepts of “slightly injured” (someone whose condition requires between 0 and 6 days of hospitalisation or medical treatment) and “seriously injured” (someone whose condition requires more than 6 days of hospitalisation), which had been in use until the end of 2004, were replaced with two new concepts: “injured not hospitalised” and “injured hospitalised”. Someone who is “injured not hospitalised” receives medical treatment but is not admitted to hospital as an inpatient for more than 24 hours, while someone who is “injured hospitalised” is admitted to hospital as an inpatient for more than 24 hours. The term “unscathed” refers to people involved in, but not injured in, an accident.

Fires

A fire is a combustion reaction that produces a flame (defined as such in order to exclude smoke emissions without a fire, and other incidents that could be construed as being a fire, such as a blown turbo).

Uncertainty rate

An uncertainty rate is the probability that the result of a multiple regression analysis (see 8.2) could be produced by chance. For instance, a 1‰ uncertainty rate means that the result has less than a one-in-one-thousand possibility of being due to chance. The influence of each parameter was also quantified. In this document, a result is considered statistically significantif it has an uncertainty rate of less than 6%.

Ramp and slope

By convention,[1] the term “ramp” refers to an ascending gradient and the term “slope” refers to a descending gradient.

1.4 SCOPE OF THE RESULTS

For the purpose of this study, CETU chose to include tunnels over 300 metres long and in categories D3 and D4 in terms of the degree of monitoring.[2] D1 and D2 tunnels were omitted from the study[3] because not all breakdowns and accidents (of certain types) can be recorded in structures of these categories.[4]

Some 21 operators agreed to CETU’s request to participate in the study, representing 25 control stations in total.

1. See chapter 4 of CETU’s Booklet on geometry.
2. Referring to paragraph 5.1.1 – Degrees of permanent human presence and monitoring in IT 2000.
3. With the exception of tunnels equipped with surveillance cameras and where feedback was sufficient.
4. Category D1 and D2 tunnels are not continuously monitored, meaning that incidents are only detected when a technical alarm is triggered or a user makes an emergency call.

The dataset therefore covers 96 tunnels, representing more than 70% of French tunnels over 300 metres long by linear distance. These tunnels are categorised as one-way/twoway and urban/non-urban as per the definitions used in the Technical Instruction (IT 2000). The number of tunnels is shown in Table 1.

Tunnel type	No. of tunnels
All	96
One-way	74
Two-way	22
Urban	53
Non-urban	43

Table 1: No. of tunnels per IT 2000 category

In the interest of consistency across information sources and for reasons of data reliability, the study covers incidents occurring between 2002 and 2011.

Following harmonisation and sorting, the initial dataset containing tens of thousands of incidents was narrowed down to a representative sample of 24,483 incidents.

The distribution of these incidents between breakdowns, accidents and fires is shown in Table 2.

No. of incidents included in the dataset		
Breakdowns	**Accidents**	**Fires**
19,467	4,839	177
24,483		

Table 2: Details of the no. of events in the statistical sample

As explained in the Appendix (section 7), some periods were excluded for certain structures when calculating the incident rate, in order to ensure that the underlying data were as reliable as possible. As a result, the traffic (veh.km) used to calculate the rates may vary across incident types.

2

BREAKDOWNS IN TUNNELS

All of the results are based on the statistical sample (see 1.4).

2.1 BREAKDOWN RATE

The study revealed a breakdown rate in tunnels of 279/10^8 veh.km. This result was arrived at using the formulas explained in the Appendix (section 8.1).

Further details of the data used to calculate the rate, and the size of the statistical sample, are given in Table 3.

No. of incidents	Traffic [10^8 veh.km]	Rate (breakdowns/ [10^8 veh.km])
19,497	69.82	279

Table 3: Breakdown rate in road tunnels and data used for the calculation

2.2 PARAMETERS INFLUENCING THE BREAKDOWN RATE

This section outlines those parameters with a demonstrably significant influence on the breakdown rate according to the dataset and associated statistical analyses. Only those parameters identified through multiple regression analyses have been included, i.e. those that influence the rate independently of the others. An uncertainty rate is systematically attributed to each of these parameters (see 1.3).

2.2.1 Urban/non-urban

Urban tunnels are associated with a higher breakdown rate than non-urban tunnels, with an uncertainty rate of 1‰, reflecting a highly significant influence.

This result can be explained by the fact that vehicles are more likely to change speed suddenly, stop more frequently and break more sharply in urban environments. These manoeuvres place greater strain on the vehicle's mechanical components, leading to more frequent breakdowns.

The influence of this parameter (urban/non-urban) is quantified in Table 4, which shows the coefficients that should be applied to the average rate in Table 3.

Tunnel type	Breakdown rate coefficient
Urban	1.1
Non-urban	0.5

Table 4: Quantification of the influence of the urban nature of tunnels on the breakdown rate

2.2.2 Vehicle type

The proportion of heavy goods vehicles (HGVs) in traffic affects the overall breakdown rate, with an uncertainty rate of 1‰, reflecting a highly significant influence. A higher proportion of HGVs in traffic translates into a higher overall breakdown rate.

This result can be explained by the fact that the breakdown rate among HGVs is typically higher than the breakdown rate among light vehicles (LVs). This is because, relative to LVs, HGVs are considerably heavier and make much longer journeys, which places greater strain on their mechanical components. Moreover, although HGVs are subject to stricter maintenance and servicing requirements, these rules may not always be followed.

The statistical sample reveals that the breakdown rate among HGVs is 1.4 times higher than the breakdown rate among LVs. These rates are shown in Table 5.

Breakdown rate (breakdowns/[10^8 veh.km])		
All vehicles	Light vehicles (LVs)	Heavy goods vehicles (HGVs)
279	268	390

Table 5: Breakdown rate per vehicle type based on the statistical sample

2.2.3 Tunnel gradient

The tunnel gradient affects the breakdown rate, with an uncertainty rate of 1‰, reflecting a highly significant influence.

	Tunnel gradient	Breakdown rate coefficient
Slope	– 5%	0.6
	– 4%	0.7
	– 3%	0.7
	– 2%	0.8
	– 1%	0.9
Ramp	0%	1
	1%	1.3
	2%	1.7
	3%	2.1
	4%	2.7
	5%	3.5

Table 6: Quantification of the influence of tunnel gradient on the breakdown rate

The breakdown rate rises as the ramp increases and falls as the slope increases.[5]

This result can be explained by the fact that travelling uphill places greater strain on the vehicle's mechanical components, especially the engine.

This influence is quantified in Table 6 and represented in Figure 1:

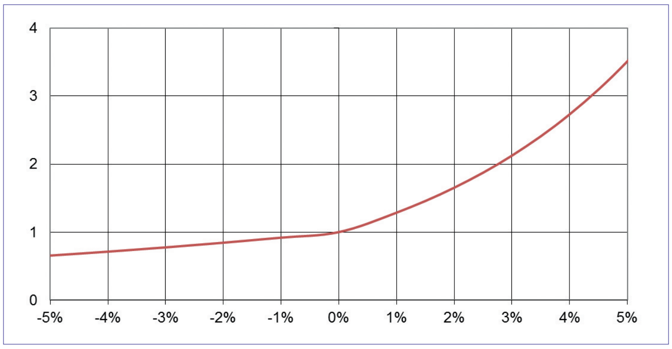

Figure 1: Change in breakdown rate according to tunnel gradient

2.3 COMPARISON WITH BREAKDOWN RATES IN THE OPEN AIR

It was only possible to use breakdown-related data for the open-air motorway network.

The Association of French Motorway Companies (ASFA) publishes an annual document containing key figures on the operations of motorway companies. Using these annual reports, it was possible to calculate average breakdown rates on the French motorway network between 2008 and 2011. Although these rates include data relating to tunnels on the network, the length of tunnels is extremely small relative to the length of the open-air network. As such, these rates can be considered representative of the open-air portion of the network only.

The breakdown rates for the French motorway network and tunnels are shown in Table 7.

	Average breakdown rate (breakdowns/[10^8 veh.km])	
	Tunnels (2002-2011)	Open air (motorways, 2008-2011)
HGVs	**390**	**323**
LVs	**268**	**419**
Total	**279**	**405**

Table 7: Average breakdown rates in tunnels and in the open air

For the sake of consistency, the tunnel rates shown in Table 7 are the same as those set out in Table 5 in section 2.1 of this document, covering the period 2002-2011. The tunnel rates for the period 2008-2011 only are slightly different, as follows: HGVs: 395; LVs: 262; total: 273. These rates are used in Figure 2.

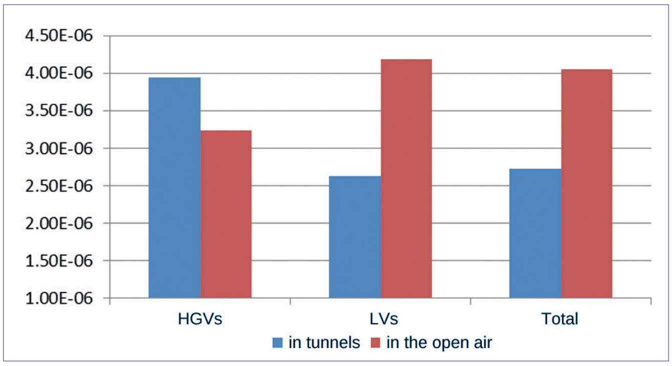

Figure 2: Average breakdown rates in tunnels and in the open air (motorways), 2008-2011

The breakdown rates for overall traffic and LVs are lower in tunnels than on the open-air motorway network. This difference can be explained by a preference, among users, to stop and get out of their vehicle outside a tunnel wherever possible. This is also a general instruction that applies to almost all structures, and one that is stressed in driver training courses.

Conversely, the breakdown rate for HGVs is higher in tunnels than on the open-air motorway network. The difference, which is small for this order of magnitude (difference of 72 breakdowns per 108 veh.km, or around 19%), can be explained by the large number of tunnels located in mountainous areas, where steep roads place greater strain on mechanical components.

5. See 5 for a definition of "ramp" and "slope".

3

ACCIDENTS IN TUNNELS

This section looks first at all accidents together (personal injury accidents and physical damage), before focusing specifically on personal injury accidents (paragraph 3.3). All of the results are based on the statistical sample (see 1.4).

3.1 ACCIDENT RATE IN TUNNELS

In tunnels, the accident rate is 41/10^8 veh.km. This result was arrived at using the formulas explained in the Appendix (section 8.1).

Further details of the data used to calculate the rate, and the size of the statistical sample, are given in Table 8.

No. of incidents	Traffic[6] [10^8 veh.km]	Rate (accidents/ [10^8 veh.km])
4,839	116.72	41

Table 8: Accident rate in road tunnels and data used for the calculation

3.2 PARAMETERS INFLUENCING THE ACCIDENT RATE

This section outlines those parameters with a demonstrably significant influence on the accident rate according to the dataset and associated analyses. As with breakdowns, only those parameters identified through multiple regression analyses have been included. To recap, an uncertainty rate is systematically attributed to each of these parameters (see 1.3).

3.2.1 One-way/two-way

One-way tunnels are associated with a higher accident rate than two-way tunnels, with an uncertainty rate of 1‰, reflecting a highly significant influence.

This apparently counter-intuitive result can be explained by two factors – the number of lanes in the tunnels and user behaviour:

- **Number of lanes:** overtaking is normally permitted (at least for LVs) in tunnels with more than one lane per direction. Overtaking can cause vehicles to collide with one other. With a handful of exceptions, the vast majority of one-way tunnels in France feature more than one lane per direction, whereas two-way tunnels have just one lane per direction. This was true of the tunnels included in the statistical sample. In two-way tunnels, there is of course a risk of a head-on collision between vehicles travelling in opposite directions. But such incidents occur extremely rarely in two-way tunnels (in 2017, for instance, there were 58 personal injury accidents in the 94 tunnels on the French national road network, but only two of these accidents involved head-on collisions between vehicles in two-way tunnels). The influence of the number of lanes on the accident rate was confirmed using multiple regression analyses ;
- **User behaviour:** road safety experts have repeatedly observed lower accident rates on stretches of road that drivers consider to be less safe, or even dangerous. Analyses have shown that, in these locations, the perceived lack of safety prompts users to adopt more cautious behaviour which tends to limit the number of accidents (such as greater respect of the speed limit and/or safety distance between vehicles and/or better compliance with signs). Drivers often perceive two-way tunnels as less safe, or even dangerous, since they require them to keep to a single lane between a side wall and oncoming vehicles (including HGVs).

The statistical sample reveals that the accident rate in one-way tunnels is 1.8 times higher than the accident rate in two-way tunnels. These rates are indicated in Table 9.

Accident rate (accidents/[10^8 veh.km])	
One-way tunnels	Two-way tunnels
44	25

Table 9: Accident rates in one-way and two-way tunnels based on the statistical sample

6. This finding is based on different traffic data than the breakdown rate. This is because, prior to installing modern data-input and/or monitoring equipment, some operators focused on collecting information about the most severe types of incident (fires and accidents, in descending order of priority).

3.2.2 Tunnel gradient

The tunnel gradient[7] affects the accident rate, with an uncertainty rate of 1%.

The accident rate increases as the ramp or slope becomes steeper.

This result can be explained by the fact that:

- the difference in speed between LVs and HGVs can be greater on steeper ramps;
- steeper slopes can result in higher speeds overall.

This influence is quantified in Table 10 and represented in Figure 3.

Tunnel gradient (ramp or slope)	Accident rate coefficient
0%	0.9
1%	1.00
2%	1.05
3%	1.15
4%	1.25
5%	1.35

Table 10: Quantification of the influence of tunnel gradient on the accident rate

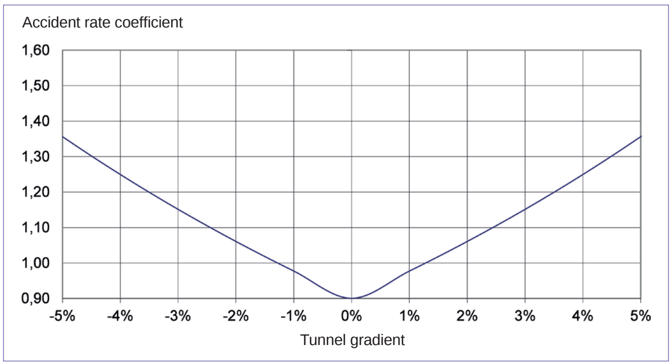

Figure 3: Change in accident rate according to tunnel gradient

3.2.3 Presence of interchanges

The presence of interchanges inside the tunnel or in its immediate vicinity[8] affects the accident rate, with an uncertainty rate of 5%.

This result can be explained by the fact that an interchange causes vehicles to change lane on either side of its position, as well as causing drivers to enter and/or exit the flow of traffic. These manoeuvres can result in side-impact and/or rear-end collisions between vehicles, as well as resulting in vehicles colliding with the structure of the tunnel itself.

The influence of the presence of interchanges on the accident rate in tunnels is quantified in Table 11.

Presence of interchanges	Accident rate coefficient
No interchange	**1**
Less than 500 m from the tunnel	**1.2**
Inside the tunnel	**1.4**

Table 11: Quantification of the influence of the presence of interchanges on the accident rate

7. See section 1.3 for the definition of ramp and slope.
8. The influence of interchanges outside the tunnel (up to 500 metres from the portals) was assessed.

3.3 PERSONAL INJURY ACCIDENTS

3.3.1 Personal injury accident rate

In road tunnels, the personal injury accident rate is **8 accidents/ 10^8 veh.km**.

Since personal injury accidents were not systematically distinguished from other types of accident, the statistical analysis was only run on a subset of the data where these accidents had been documented. The result shows that, over the period in question (2002-2011), personal injury accidents accounted for approximately 20% of all accidents.

3.3.2 Parameters influencing the personal injury accident rate

As with accidents as a whole, only those parameters identified through multiple regression analyses have been included. To recap, an uncertainty rate is systematically attributed to each of these parameters (see 1.3).

The one-way/two-way nature of the tunnel and its slope influence the personal injury accident rate, as was the case for all accidents. However, the proportion of HGVs in the traffic is an influencing parameter specific to the personal injury accident rate. These three parameters are discussed in detail below.

Interestingly, the presence of interchanges inside or in the vicinity of a tunnel influences the rate of accidents as a whole but does not influence the rate of personal injury accidents.

One-way/two-way

As is the case for accidents as a whole, one-way tunnels are associated with a higher personal injury accident rate than two-way tunnels, with an uncertainty rate of 1‰, reflecting a highly significant influence. Again, this influence can be explained by the number of lanes in the tunnels and by user behaviour (see 3.2.1).

The statistical sample also reveals that the personal injury accident rate is 1.8 times higher in one-way tunnels than in two-way tunnels.

Tunnel gradient

As is the case for accidents as a whole, the tunnel gradient[9] affects the personal injury accident rate, with an uncertainty rate of 1%, reflecting a significant influence.

The personal injury accident rate also rises as the absolute gradient value increases, again for the same reasons: the difference in speed between LVs and HGVs on steeper ramps, and increased speeds in general on slopes (see 3.2.2).

In quantitative terms, there is only a slight difference in the influence of gradient on the personal injury accident rate and the accident rate as a whole (see Table 10), and only for ramps with gradients of 0% and 2% (coefficients of 0.92 and 1.08 respectively).

Vehicle type

The proportion of HGVs in traffic affects the personal injury accident rate, with an uncertainty rate of 5%. A higher proportion of HGVs in traffic translates into a higher personal injury accident rate. This result can be explained by the fact that accidents involving HGVs are generally more serious than collisions in which this vehicle type is not involved, since a HGV has a much higher level of mechanical energy than an LV.

This influence is quantified in Table 12.

Proportion of HGVs in traffic	Personal injury accident rate coefficient
0%	1.00
1%	1.02
2%	1.05
5%	1.12

Table 12: Quantification of the influence of HGVs on the personal injury accident rate

3.3.3 Severity

The severity of personal injury accidents in French road tunnels between 2002 and 2011 is quantified in Table 13.

	Rate (number/[10^8 veh.km])	Number/ personal injury accident
Injured	**10.4**	**1.3**
Killed	**0.3**	**0.04**

Table 13: Quantification of severity in tunnels for the period 2002-2011

Injuries are divided into two categories: “injured hospitalised” and “injured not hospitalised” (see 1.3).

At the 14 control stations where this distinction was made, the share of “injured hospitalised” casualties is around 8%.

9. See 5 for a definition of “ramp” and “slope”.
10. Severity information is not always available for personal injury accidents in tunnels. This is likely why the injury rate is lower than the personal injury accident rate.

3.3.4 Comparison with the open air

Each year, the National Interministerial Road Safety Observatory (ONISR) publishes an annual report on road safety in France. Using these annual reports, it was possible to calculate average rates of accidents, injuries and fatalities across the entire road network in mainland France between 2007 and 2011. Although these rates include data relating to tunnels on the network, the length of tunnels is extremely small relative to the length of the open-air network. As such, these rates can be considered representative of the open-air portion of the network only.

The rates of personal injury accidents, injuries and fatalities on the French open-air road network, and the rates for road tunnels, are presented in Table 14.

	Personal injury accidents/[10^8 veh.km]	Injuries[10]/ [10^8 veh.km]	Fatalities/ [10^8 veh.km]
Tunnels 2002-2011	8	10.4	0.3
Open air 2007-2011	13.1	16.4	0.76

Table 14: Rates of personal injury accidents, injuries and fatalities in tunnels and in the open air

For the sake of consistency, the tunnel rates shown in Table 14 are the same as those set out in sections 3.3.1 and 3.3.3 of this document, covering the period 2002-2011. The tunnel rates for the period 2007-2011 only are slightly different, but the results of the comparison with the open-air network remain unchanged. These rates are as follows: personal injury accident rate: 8.84; injury rate: 6.86; fatality rate: 0.21. These rates are used in Figure 4.

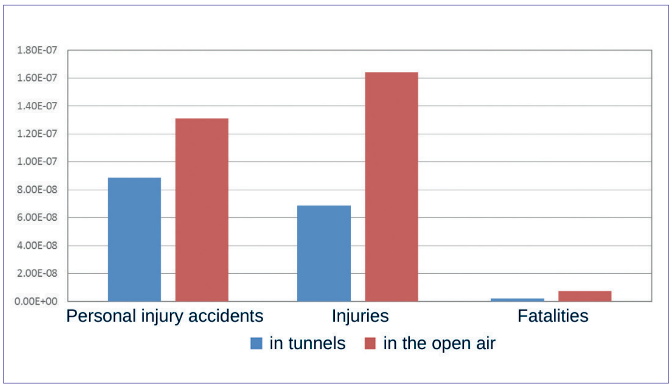

Figure 4: Rates of personal injury accidents, injuries and fatalities in tunnels and in the open air, 2007-2011

As Table 14 and Figure 4 show, personal injury accident and casualty rates are lower in tunnels than in the open air. The personal injury accident rate is 1.5 times higher in the open air than in tunnels, while the fatality and injury rates are 3.7 and 2.4 times higher in the open air than in tunnels respectively.

This result can be explained by the fact that, on open-air sections of road, there may be other factors contributing to accidents that are rarely or never found in tunnels, such as intersections, sharp and/or successive bends, access or exit ramps, and high-speed sections.

User behaviour is another explanatory factor, with drivers likely to be more cautious in tunnels than in the open air (due to the confined nature of the space).

4

FIRES IN TUNNELS

All of the results are based on the statistical sample (see 1.4).

4.1 FIRE RATE IN TUNNELS

The study revealed a fire rate in tunnels of 1.1 per 10^8 veh.km. This result was arrived at using the formulas explained in the Appendix (section 8.1).

Further details of the data used to calculate the rate, and the size of the statistical sample, are given in Table 15.

No. of incidents	Traffic[11] [10^8 veh.km]	Rate (fires/ [10^8.veh.km])
177	167,6	1,1

Table 15: Fire rate in road tunnels and data used for the calculation

4.2 PARAMETERS INFLUENCING THE FIRE RATE

This section outlines those parameters with a demonstrably significant influence on the fire rate according to the dataset. As with breakdowns and accidents, only those parameters identified through multiple regression analyses have been included. To recap, an uncertainty rate is systematically attributed to each of these parameters (see 1.3).

4.2.1 Vehicle type

The proportion of HGVs in traffic affects the overall fire rate, with an uncertainty rate of 5.1%. A higher proportion of HGVs in traffic translates into a higher overall fire rate.

This result can be explained by the fact that the fire rate among HGVs is higher than the fire rate among LVs. This is because, relative to LVs, HGVs place greater strain on their mechanical components. In addition, because HGVs make much longer journeys, they often have electrical equipment (audiovisual systems and household appliances) installed in their cabs, which are potential sources of fire. These specific features make HGVs more liable to spontaneous combustion, leading to a higher fire rate.

The statistical sample reveals that the fire rate is 3.3 times higher among HGVs than among LVs. These rates are shown in Table 16.

Fire rate (fires/[10^8 veh.km])	
Light vehicles (LVs)	Heavy goods vehicles (HGVs)
0.9	2.9

Table 16: Fire rates among LVs and HGVs based on the statistical sample

4.2.2 Tunnel gradient

The tunnel ramp[12] affects the fire rate, with an uncertainty rate of 5%.

The fire rate increases as the ramp becomes steeper. This result can be explained by the fact that travelling uphill places greater strain on the vehicle's mechanical components, especially the engine. This strain can cause these components to become hot or to malfunction, potentially causing a fire to break out.

11. This finding is based on different traffic data than the breakdown rate. This is because, prior to installing modern data-input and/or monitoring equipment, some operators focused on collecting information about the most severe types of incident (fires and accidents, in order of priority).
12. See 1.3 for a definition of "ramp" and "slope".

This influence is quantified in Table 17 and represented in Figure 5.

Tunnel gradient (ramp or slope)	Fire rate coefficient
≤ 0%	0.9
1%	1.05
2%	1.2
3%	1.45
4%	1.65
5%	1.95

Table 17: Quantification of the influence of tunnel gradient on the fire rate

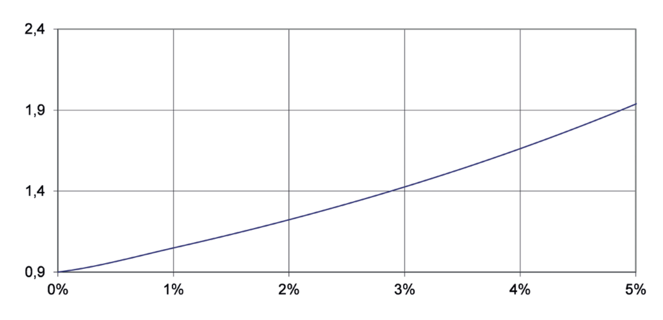

Figure 5: Change in fire rate according to tunnel gradient

4.2.3 Gradient of access routes

The gradient of tunnel access routes affects the fire rate, with an uncertainty rate of 6%.

The fire rate is higher when the tunnel access route, over a long distance, includes one or more adjacent sections with a particularly steep gradient (ramp or slope).

This result can be explained by the fact that this type of route places greater strain on the vehicle's mechanical components and brakes. This strain can cause these components to become hot or to malfunction, potentially causing a fire to break out.

The fire rate in tunnels with access ramps that are particularly steep over a long distance is around twice as high as the fire rate in tunnels without such ramps.

5

CONCLUSION

The studies carried out allowed for the breakdown, accident and fire occurrence rates to be updated and for the associated influencing parameters to be identified using multiple regression analysis.

These studies are based on incidents occurring between 2002 and 2011 in 96 tunnels representing more than 70% of French tunnels over 300 metres long by linear distance.

The **average breakdown, accident and fire rates** in road tunnels, calculated on the basis of these incidents, are shown in Table 18.

Breakdowns/ [10^8 veh.km]	All accidents/ [10^8 veh.km]	Personal injury accidents/ [10^8 veh.km]	Fires/ [10^8 veh.km]
279	41	8	1.1

Table 18: Breakdown, accident and fire rates in road tunnel

The **severity of personal injury accidents** is quantified in Table 19.

Injuries/ [10^8 veh.km]	Fatalities/ [10^8 veh.km]
10.4	0.3

Table 19: Quantification of severity in tunnel

Only those **parameters** with a demonstrably significant influence on the incidents were included (uncertainty rate of 6% or less). These are detailed below:

Breakdowns

Urban tunnels are associated with a higher breakdown rate. A coefficient of around 1.1 can therefore be applied to the average breakdown rate (see Table 18) for urban tunnels, and a coefficient of around 0.5 can be applied for non-urban tunnels.

The proportion of **HGVs** in traffic affects the overall breakdown rate: a higher proportion of HGVs in traffic translates into a higher overall breakdown rate. The breakdown rate among HGVs is around 1.4 times higher than the breakdown rate among LVs.

The tunnel gradient[13] affects the breakdown rate. The breakdown rate increases as the ramp becomes steeper. The rate falls as the slope increases. For instance, the breakdown rate is around twice as high in a tunnel with a gradient of 3% than in a tunnel with zero gradient.

Accidents

One-way tunnels are associated with a higher accident rate. The accident rate in one-way tunnels is around twice as high as the accident rate in two-way tunnels. One-way tunnels are also associated with a higher personal injury accident rate. These results can largely be explained by the number of lanes and user behaviour.

The tunnel gradient affects the accident rate. The accident rate increases as the gradient becomes steeper (in absolute terms). For instance, the accident rate is around 1.3 times higher in a tunnel with a gradient of 3% than in a tunnel with zero gradient. The tunnel gradient also affects the personal injury accident rate.

The presence of interchanges inside the tunnel or in its immediate vicinity (within 500 metres) affects the accident rate. The accident rate is around 1.4 times higher in tunnels with interchanges than in those without interchanges. However, the presence of interchanges was not identified as an influencing factor for the personal injury accident rate.

The proportion of **HGVs** in traffic affects the **personal injury accident** rate. A higher proportion of HGVs in traffic translates into a higher personal injury accident rate. For instance, the personal injury accident rate is around 1.12 times higher in a tunnel where HGVs account for 5% of traffic than in a tunnel where there are no HGVs.

Fires

The proportion of **HGVs** in traffic affects the overall fire rate, with an uncertainty rate of 5.1%. A higher proportion of HGVs in traffic translates into a higher overall fire rate. The fire rate is around 3.2 times higher among HGVs than among LVs.

13. See 1.3 for a definition of “ramp” and “slope”.

The tunnel ramp[14] affects the fire rate. The fire rate increases as the ramp becomes steeper. The fire rate is around 1.6 times higher in a tunnel with a gradient of 3% than in a tunnel with zero gradient.

The gradient of tunnel access routes affects the fire rate. The fire rate is higher when the tunnel access route, over a long distance, includes one or more adjacent sections with a particularly steep gradient (upwards or downwards). The fire rate in tunnels with access routes that are particularly steep over a long distance is around twice as high as the fire rate in tunnels without such ramps.

Further details, including a discussion of the explanatory factors behind these influencing parameters and the associated uncertainty rates, can be found in sections 2.2 (breakdowns), 3.2 (accidents), 3.3.2 (personal injury accidents) and 4.2 (fires).

Comparison with the open air

Based on available data, it was possible to **compare tunnel and open-air statistics.** The main insights drawn from this comparison are detailed below:

- The breakdown rates for overall traffic and LVs are lower in tunnels than on the open-air motorway network, but the opposite is true of the breakdown rate for HGVs (see 2.3).
- The personal injury accident and casualty rates are lower in tunnels than in the open air (see 3.3.4).

Treatment of biases

As with any study based on field data, the use of sophisticated methods does not remove the risk that the results could be affected by **biases**. First of all, different operators record incidents – especially breakdowns – in different ways. The data collected, the degree of detail and the associated definitions may be inconsistent from one operator to the next, for instance due to the human and material resources assigned to this task. There may also be inconsistencies in the data review and verification process. During the period covered by the studies (2002-2011), changes in equipment (especially video systems) and/or operator and personnel organisation occurred, with a potential impact on data collection and processing. Lastly, as with any human activity, errors may have occurred in the data collection and verification process.

It should be noted, however, that potential biases are less of a problem for the most severe incidents, since operators pay particular attention to such incidents. Moreover, the impact of these biases was limited during the studies by verifying and cross-referencing the information.

14. See 5 for a definition of “ramp” and “slope”.

6

APPENDIX 1 COMPARISON OF NEW RATES AGAINST HISTORICAL BASELINES

6.1 BREAKDOWN, ACCIDENT AND FIRE RATES IN THE 1998 REPORT

The breakdown, accident and fire rates in the 1998 report are shown in Table 20, along with the new rates given in this document.

Rate	Breakdowns/ [10^8 veh.km]	Accidents/ [10^8 veh.km]	Personal injury accidents/ [10^8 veh.km]	Fires/ [10^8 veh.km]
1998 report	**530**	**70**	**20**	**3**
2021 information document	**279**	**41**	**8**	**1.1**

Table 20: Breakdown, accident and fire rates in the 1998 report and the new rates

As Table 20 shows, the new rates are lower than the 1998 baselines across the board. This reduction is consistent with the observed trend in the open air. There are several possible reasons for this trend, including safety initiatives by owners, tunnel operators and other stakeholders, ongoing enhancements in vehicle safety and reliability, improved user information and awareness (on road safety in general and tunnel-specific behaviour in particular), and tougher enforcement and penalties.

However, care should be taken not to draw any conclusions from this comparison, since the new rates are based on a much more representative and robust sample (in terms of the number of tunnels and the period covered by the data) than the 1998 baselines, as detailed below.

The new rates are based on a sample of 96 tunnels and data covering a period of around 10 years (see 1.4). The 1998 rates, meanwhile, were calculated using a sample of 38 tunnels (with highly uneven distribution in terms of tunnel types – see Table 21). Moreover, the data covered vastly different periods from one tunnel to the next, ranging from two years in some cases to 10 years in others. The data spanned five years for 78% of the tunnels on motorways under private management.

Tunnel type	No. of tunnels
All	38
Large two-way tunnels	2
Tunnels on motorways under private management	23
Urban and suburban tunnels	11
Urban two-way tunnels	2

Table 21: No. of tunnels per IT 2000 category

6.2 FIRE RATE IN BOOKLET 4 OF THE GUIDE TO ROAD TUNNEL SAFETY DOCUMENTATION

Booklet 4 of the Guide to Road Tunnel Safety Documentation explains the role of the specific hazard investigation in the safety documentation and outlines the recommended methodology. The appendix to the booklet also contains practical recommendations and standardised values for certain parameters, to assist those overseeing or conducting this type of study. Fire rates are included in these values. The rates for LVs and HGVs[15] are given (other than for “non-standard” cases) in Table 22, along with the new rates.

	Booklet 4 (fires/ [10^8 veh.km])	2021 information document (fires/[10^8 veh.km])
LVs	**2**	**0.9**
HGVs and coaches	**[1.5 – 4.5]**	**2.9**
Of which not controlled	**[0,5 – 1,5]**	**–**

Table 22: Fire rates in booklet 4 and new fire rates

15. Booklet 4 also gives rates for the carriage of dangerous goods. However, this type of transport was not examined in the study that produced the new rates because of a lack of data.

Table 22 shows that the new fire rate for LVs is lower than the rate given in booklet 4. This reduction is likely due to improvements in vehicle reliability and servicing since booklet 4 was published in 2003, and most vehicle fires are mechanical in origin.

Similar improvements have occurred in relation to HGVs. However, increases in tonnage transported and journey length are such that the risk of fire is greater for this vehicle type. Section 4.2.1 of this document showed that the proportion of HGVs in traffic affects the overall fire rate. A higher proportion of HGVs in traffic translates into a higher overall fire rate because these vehicles are heavier and travel longer distances than LVs. This is likely why the new rate is still within the range of values given in booklet 4, albeit slightly closer to the minimum value.

The new rates can therefore only be used for HGVs if specific local characteristics justify the use of a higher value, within the range given in booklet 4.

If the benchmark fire rates given in this document are used because sufficiently robust local statistics are not available, then the influencing parameters (tunnel ramp, gradient of access routes – see 4.2) should also be used in order to refine the results.

7

APPENDIX 2 DATA COLLECTION AND CONSOLIDATION PROCESS

The data were collected from various sources, which differed according to the operator, the control station and the tunnel itself.

Incident-related information was extracted from:

- paper incident logs kept by control station operators;
- electronic incident databases;
- quarterly, half-yearly and annual operation reports;
- tunnel closure reports;
- tunnel incident response reports;
- the "list of significant incidents and accidents" (part of the safety documentation);
- centralised feedback forms completed by the operator on the CETU website;
- press articles (for major incidents).

Information about tunnel characteristics was provided by operators or extracted from safety documentation or other documents supplied.

Once the data had been collected for each operator, they were exported into three separate national databases – one for each incident type (breakdowns, accidents and fires).

Some data were excluded when calculating the rates because the inherent uncertainties were judged to be too high.

The data were also filtered as part of a critical analysis in order to guarantee the reliability of the calculated rates. In particular, the following operations were performed in sequence:

- searching for duplicates;
- re-qualifying certain events;
- cross-referencing against the forms submitted to CETU;
- requesting additional information from the operator and cross-referencing against media articles for major incidents (fires and the most severe personal injury accidents);
- excluding data from some years where there was excessive disparity relative to the rest of the dataset (e.g. far fewer events) that could not be justified. The excluded years vary across different incident types and, of course, across tunnels. For instance, the year(s) in question may correspond to periods when there were no video surveillance or automatic incident detection systems in place.

8 APPENDIX 3 DETAILS OF THE STATISTICAL METHODS USED

This appendix details the formulas and methods used by consulting firm BG Ingénieurs Conseils, with support from the École Polytechnique Fédérale de Lausanne (EPFL), in carrying out the study (see 1.2).

8.1 INCIDENT RATE CALCULATIONS

The calculated rates for each year (hereafter the "annual rates") are based on the included tunnels and years only (see 7). As such, these rates do not always relate to the same tunnels (since some tunnels were excluded from the dataset for certain years).

In order to calculate a rate for each year, the annual rate per incident type was calculated based on all tunnels where the year in question was judged to be representative.

For incident type E and period A, the formula used was therefore as follows:

$$\frac{\sum_{\text{Tunnels } T} \text{no. of incidents}_{E.A.T} \times R_{E.A.T}}{\sum_{\text{Tunnels } T} \text{vehicles} \cdot \text{km}_{A.T} \times R_{E.A.T}}$$

where $R_{E.A.T}$ was equal to 1 if the data for incidents of type E occurring in period A in tunnel T were deemed to be sufficiently exhaustive, and 0 if this was not the case. This calculation principle was applied regardless of the period considered.

8.2 IN-DEPTH STATISTICS ANALYSES – MULTIPLE REGRESSIONS

Whereas simple statistical analyses only allow a single parameter to be isolated for further investigation, with in-depth statistical (regression) analyses it becomes possible to examine the influence of multiple parameters at once and to isolate the influence of each of these parameters.

These analysis methods, which require the use of more complex tools, can be used to confirm or adjust the conclusions of simple analyses. The in-depth statistical analyses examined the same parameters as the simple analyses, for breakdowns, accidents and fires.

The following sub-sections explain:

- why the regression analyses were performed and which statistical models were chosen;
- which parameters were analysed per incident type;
- how the significance of the results was assessed.

Regression analyses: aim and statistical models

The aim of the regression analysis is to develop a formula that, based on a given number of parameters specific to a tunnel (over a given period), provides a reliable estimation of the number of incidents (breakdowns, accidents or fires). This formula will then give an indication as to the influence of each of these parameters. The formula is based on a statistical model.

Various types of statistical model can be used to simulate the occurrence of random events such as breakdowns, accidents and fires.

The following models were applied to the issue of incidents in tunnels:

- Poisson regression;
- Quasi-Poisson regression;
- Negative binomial regression.

Poisson regression is particularly well-suited to rare events, such as the incidents examined in this study, which occur rarely relative to the number of vehicles passing through a tunnel.

Quasi-Poisson and negative binomial regressions can be used for over-dispersed count data, i.e. when variance exceeds the level predicted by a simple Poisson regression. This overdispersion, which is often caused by the influence of other, second-order factors that are not included in the statistical analyses, is observed for breakdowns and accidents, but not for fires, which are far fewer in number.

Using a diverse range of models and evaluation tools (statistical tests) allows the reliability of the estimated parameters to be improved and assessed.

Each model provides satisfactory results. For each incident category, the most appropriate regression model is determined by:

- performing multiple regressions using the methods outlined above;
- analysing the "residuals" of the regressions in order to determine the quality of the model;
- selecting the most appropriate model and using the results of that model.

The results of the study are based on the most appropriate model only. However, all suitable models for each incident type were studied in order to ensure that the final results were accurate as possible (best match between model and data).

Chosen parameters

It was not possible to run an in-depth statistical analysis on all the parameters in the dataset.

There were two possible reasons for this:

- not enough data had been collected about this parameter (e.g. amount of traffic when the incident occurred, cause of the incident, etc.);
- there was little or no causal relationship between the parameter and the occurrence of the events (e.g. relationship between the presence of closure barriers at the tunnel portals and breakdowns).

The filtering exercise resulted in a long list of parameters that were then examined via in-depth statistical analysis. In some cases, the analysis revealed that the parameter had no influence on the occurrence of events.

Significance of the results of the in-depth statistical analysis: definition

In in-depth statistical analysis, a result is considered statistically significant when it is unlikely that the same result could be produced by chance. In order to determine the significance of a result, an uncertainty rate is calculated. This rate expresses the probability that the result in question could be produced by chance.

For example, a 5% uncertainty rate means that the result has a less than 5% possibility of being due to chance. The lower the uncertainty rate, the greater the credit given to the corresponding result.

A result is considered statistically significant if it has an uncertainty rate of less than 6%.

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