Nat. Hazards Earth Syst. Sci. Discuss., 1, 1285–1317, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/1285/2013/
doi:10.5194/nhessd-1-1285-2013

Natural Hazards
and Earth System
Sciences
Open Access
Discussions

Dynamic risk simulation to assess risk along roads

J. Voumard[1], O. Caspar[2], M.-H. Derron[1], and M. Jaboyedoff[1]

[1]Research Centre on Terrestrial Environment, University of Lausanne, Lausanne, Switzerland
[2]Touring Club Suisse, Geneva, Switzerland

Received: 28 February 2013 – Accepted: 22 March 2013 – Published: 17 April 2013

Correspondence to: J. Voumard (jeremie.voumard@unil.ch)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Risk generated by natural hazards on roads is usually calculated with equations integrating various parameters related to hazard and traffic. These are static variables, like a rockfall hazard estimation for a road section or the average number of vehicles crossing this section every day. This methodology cannot take into account dynamic variations of traffic and interactions between vehicles such as speed modifications due to the sinuosity, slowdowns resulting of saturated traffic or vehicles columns forming in front of traffic lights.

The influence of traffic dynamics on the risk estimation is not assessed with standard methodologies. Here we show, by mean of a dynamic traffic simulator, that the traffic variations may greatly influence the risk estimation over time. The risk is analysed on several alpine road sections in Switzerland using a dynamic vehicles approach and compared with the results of the static methodology. It demonstrates that risk significantly increases on sinuous sections because of the decreasing of vehicles speed.

A more realistic risk can be obtained from a dynamic approach especially on mountain roads. A dynamic traffic simulator, modelling interactions between vehicles is a helpful tool to support decision making to reduce risk on roads.

1 Introduction

Roads, especially in the mountains, are frequently exposed to rockfalls (Budetta, 2004; Bunce et al., 1997). The risk assessment for rockfalls on a highway network is not obvious because the risk depends on several factors such as event frequency, average vehicle speed, decision sight distance, road characteristics and traffic on each road section (Budetta, 2004). Two probabilities, block release and propagation, are usually combined to estimate the hazard of rockfall (Dorren, 2003, 2011; Jaboyedoff and Labiouse, 2011; Jaboyedoff et al., 2012).

Different methodologies are proposed to estimate the rockfalls hazard from the regional scale to the local scale. Michoud et al. (2012) propose a rockfall hazard assessment at a regional scale while Guzzetti et al. (2003) offer the same type of evaluation at a subregional scale. Rockfall hazard assessment methodologies at a local scale are proposed by Baillifard et al. (2003), Budetta (2004), Pierson (1990) and Corominas and Moya (2008). Risk Assessment Methods (RAM) of rockfall hazard threatened highways are proposed by Fell et al. (2005), Budetta (2004), Hungr et al. (1999) and Corominas et al. (2005) proposing a Quantitative Risk Assessment (QRA).

Some methodologies to evaluate the risk on major highways have been proposed by governmental roads agencies or by specialists which methods were taken by governmental agencies like in Switzerland (Borter, 1999; Cajos et al., 2009), and USA (Pierson et al., 1990; Roberds, 2005) or within international research projects like MASSA (2010) (Medium And Small Size rock fall hazard Assessment) in Switzerland, Italy and France. Other methodologies enable to make costs/benefits analysis in the case of a closed road (Wilhelm, 1997).

All of these methods use static traffic values to assess the risk. The number of vehicles on a road section is generally defined by an average number of vehicles per time unit (daily or annually) and the vehicles speed is the same for each of them. Two risks are generally calculated: (1) the object risk which is the probability that a driver is killed among the total amount of persons passing through the dangerous area; (2) the individual risk which is the probability that a driver passing N times per day in a dangerous area is killed. This article focuses on the object risk.

All equations for this study are based on the usual risk equation (Einstein, 1988; Fell et al., 2005):

$$R = \sum_{i=1}^{n} H \cdot \mathrm{Exp}_i \cdot V \cdot W \tag{1}$$

where R is the risk [dead/year] or [\$ yr^{-1}] with n objects, H is the hazard [1 yr^{-1}], Exp_i is the object exposure, i.e. the probability that vehicle is hit in the hazardous area [–],

V is the object vulnerability [–] and W is the potential total loss of persons or costs: [dead] or [\$].

Based on Eq. (1), the object risk equation on a road modified from Fell (2005) and Bründl (2009) is calculated with:

$$R_{\mathrm{ob}} = F_{\mathrm{e}} \cdot P_{\mathrm{s}} \cdot N_{\mathrm{v}} \cdot \lambda \cdot \beta \tag{2}$$

where R_{ob} is the object risk [dead/year], F_{e} is the occurrence frequency of an event [$1\,\mathrm{yr}^{-1}$], P_{s} is the proportion of the hazardous section which is destroyed when a hazard occurs [–], λ is the death probability when a vehicle is damaged by a hazard [–] and β the average vehicle occupation [person/vehicle], N_{v} is number of equivalent vehicles permanently exposed in the hazardous area [vehicle nb.] (see Sect. 2.2):

$$N_{\mathrm{v}} = \frac{N_{\mathrm{v_{tot}}}}{f} \cdot \frac{l}{v} \tag{3}$$

where $N_{\mathrm{v_{tot}}}$ is average number of vehicle per day [vehicle nb./day], l is the length of the dangerous section [m], f is a conversion factor to convert [$\mathrm{km\,min}^{-1}$] to [$\mathrm{m\,day}^{-1}$] and v is the average vehicle speed [$\mathrm{km\,h}^{-1}$]. Comparing Eq. (1) and Eq. (2), F_{e} and P_{s} represent H where P_{s} allows to spread the hazard on a section. N_{v} represents the sum of exposures Exp_i. λ represents the vulnerabilty V and β the losses W.

The common equation to estimate the individual risk is:

$$R_{\mathrm{ind}} = \frac{R_{\mathrm{ob}} \cdot X}{N_{\mathrm{v_{tot}}} \cdot \beta} \tag{4}$$

where X is the daily number of time a person passing through the dangerous road section [$1\,\mathrm{day}^{-1}$]. All of these parameters are summarized in Table 1.

In this paper, we propose an assessment to integrate dynamic variables of traffic in the calculation. The aims of this approach are: (1) to better understand the influences of vehicles speed and traffic density on the risk results; (2) to evaluate the consequences of columns of vehicles induced by traffic lights or following an event like a fallen block on the lanes. A dynamic traffic simulator was developed to simulate a part of vehicles interactions for different scenarios along a real alpine road in Switzerland.

2 Methodology

2.1 Dynamic traffic simulator

Different traffic simulators were investigated to be used for this risk analysis, such as the Intelligent Driver Model (Treiber and Kesting, 2010) or the Modern Traffic Flow Theory (Kerner, 2009). Those are not adapted for a dynamic traffic risk oriented modelling because they are not designed to simulate accidents (Schönhof and Helbing, 2009; Treiber and Kesting, 2010). Therefore an original dynamic traffic model was developed within the numerical computing environment of MATLAB®.

In this model, a road is composed of two lanes, one for each direction, and vehicles can only drive on their own lane. There is no possibility for a vehicle to overtake or to move from one lane to the other. Variables are declared in the box A (Fig. 1) and are followed by a time loop where two vehicles loops are integrated, one per lane. After calculating positions of all vehicles on the lane 1 at time t (box B), the simulator calculates positions of all vehicles on lane 2 at the same time (box C). After computing positions of all vehicles at time t, vehicles are counted at the time step and stored for further calculation, time is implemented of one second and the whole process, with new vehicles positions, is calculated. Then, the cumulated time of vehicles observed in the hazardous area during a simulation is counted and graphs are produced (box D). After completing computation, the dynamic and static risks are calculated (box E) (Fig. 1).

Vehicles have initial speeds which are the combination of the maximum authorised speed on the section added with a random variation margin specific to each vehicle. On a lane, this first car adapts its speed in function of the road sinuosity and obstacle on the road (traffic lights and hazard). The following vehicles fit their speed (again with the two components: maximal authorized speed and random margin) with the road sinuosity, possible obstacle and the distance to the previous vehicle.

Three mechanisms govern the vehicles kinematics: one acceleration and two decelerations (one light, taking the foot off the accelerator and one strong, using the brake). A vehicle tends to accelerate if its speed is lower as the maximal authorised speed, if the sinuosity is low and if the distance to the previous vehicle is long enough or if the previous vehicle drives faster and if there is no obstacle on the road. A vehicle brakes in function of the visibility distance, the sinuosity of the section, the distance to the previous vehicle and the presence of an obstacle on the road. Thus, the vehicles speed depends on the traffic density, the road geometry (2-D), the previous vehicle speed and presence of obstacles on the road section (Appendix A).

All of the kinematics parameters as well as the visibility distance (not depending on topography, only on sinuosity) and speed parameters (with a total of 60 parameters) can be defined directly in the GUI (Fig. 2) or in the MATLAB®-files.

A lane is constructed as a suite of nodes connected by segments. Segments do not have to be the same length, so that nodes can be chosen according to the roads geometry. Vehicles follow the curvilinear abscissa of the lane on which they are.

2.2 Dynamic risk calculation

The main concept to calculate risk for a dynamic traffic is to measure the duration of presence of vehicles inside the hazardous area during a given time. By this way, slow vehicles which stay longer in the dangerous area are more threatened by a hazard. Thus, each vehicle presence is analysed and recognised. The simulator counts the presence of vehicles in the dangerous area by looking every second if vehicles are located in the section. It measures the cumulated time of vehicles observed in the hazardous area during a simulation time, t_{cum}, in function of time steps, vehicles number and sections number (Fig. 3):

$$t_{\mathrm{cum}} = \sum_{i=1}^{t_{\mathrm{sim}}} \sum_{j=1}^{n} \text{if } \left(x(t_i)_j \epsilon D_k \right) \Delta t \tag{5}$$

where D_k is the domain of k sections and $\Delta t = x(t_i + 1) - x(t_i)$ is constant, i is the time index, j the vehicle index and n the number of vehicles generated during the simulation.

When the simulation starts, there is no vehicle on the road (initial condition). Then the simulation time, t_{sim}, starts only when the first vehicle enters in the hazardous section. At the end of the simulation, the cumulated time of vehicles observed in the hazardous area during a simulation, t_{cum}, is divided by the duration of the simulation:

$$N_{\mathrm{v}} = \frac{t_{\mathrm{cum}}}{t_{\mathrm{sim}}}. \tag{6}$$

Thus, we obtain the equivalent number of vehicles exposed permanently in the hazardous area. For example, if we obtain a cumulated time of vehicles in the hazardous area of 120 s during a 60 s simulation, this is equivalent to two vehicles which are permanently in the hazardous area during the 60 s of simulation time. It may be twelve vehicles passing through the area during 10 s or six vehicles which stay 20 s in the hazardous section. It is not important to know how long each vehicle stays in the hazardous section but it is necessary to know the total exposure of vehicles in this section.

Therefore the dynamic object risk is equal to:

$$R_{\mathrm{ob}} = F_{\mathrm{e}} \cdot P_{\mathrm{s}} \cdot N_{\mathrm{v}} \cdot \sigma \beta = F_{\mathrm{e}} \cdot P_{\mathrm{s}} \cdot \frac{t_{\mathrm{cum}}}{t_{\mathrm{sim}}} \cdot \sigma \cdot \beta \tag{7}$$

With this approach, the vehicle velocities are removed of the equation and only the vehicle in the dangerous area are counted. This enfranchisement is fundamental for the calculation of dynamic risk. In this way, all vehicles can have their own speed and the risk depends only on the actual staying time of the vehicle in the dangerous area.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3 Case study

3.1 Description and location of case study

Eight road sections threatened by different natural hazards like rockfalls, debris flows or dolines have been studied along the mountain road Aigle – Col du Pillon in western Switzerland. Three of these sections are presented in this paper (Fig. 4) (Table 2):

1. Fontanney section with two hair pin bends is crossed by a pressure pipe which could generate debris flows in case of rupture. The major danger is that such an event might destroy a vehicles column waiting in front of a traffic light.
2. Pont-Bourquin section is threatened by an active landslide. The road forms a long curve located at the base of the landslide.
3. Col du Pillon section is located on a gypseous basement where dolines can form. In 2009, a doline destroyed a portion of the road.

3.2 Scenarios

Three different scenarios were simulated on the different road sections: (1) a road without any obstacle, (2) a road regulated by traffic lights and (3) a road with an obstacle like a block or a doline. Each road section has two lanes, one uphill and one downhill. Each simulation lasts two minutes. The scenarios are fictive but the three sectors match with danger areas and frequent engineering works.

In the first scenario (Fig. 5a), the road configuration is in a normal operational state, without any obstruction or traffic regulation. The only obstacle to the circulation is a high density of vehicles creating a slowdown. This scenario allows comparing dynamic risk calculation with the standard static method. It is useful for sections with many turns to observe the slowdown of vehicles in curves, which influences vehicles presence in dangerous area that impacts the risk. Another effect on the traffic is the different types of vehicles driving on the road, like trucks generating cars columns.

The second scenario (Fig. 5b) is caused by the presence of traffic lights on the road. This traffic regulation is often encountered on mountain roads because of the numerous road works and maintenance sites. Traffic lights can be positioned outside the dangerous area, can overlap it or can be placed inside it. It is obvious that the risk increases when vehicles are stopped in front of traffic lights located in the dangerous area. Traffic lights in Fontanney section are located inside the dangerous area. Vehicles columns in the dangerous section could in theory reach 75 m long. Traffic lights in Pont-Bourquin section are positioned outside the hazardous area because an early warning system has been installed to prevent vehicles to cross the landslide area during an event. Finally, the traffic lights of Col du Pillon section are located inside the dangerous area and are distant of only 10 m. The traffic light on the lane 1 is first green during 1 minute while the light on lane 2 is red. From 60 s to 70 s, both lights are red and after, light on lane 2 switches to green.

The third scenario (Fig. 5c) is the rarest one, involving the occurrence of a natural hazard which reaches the road. This obstacle falls on the lanes or cuts the road, blocking the traffic. The hazard can be a rockfall, a debris flow, an avalanche, a landslide, etc. Accidents number may increase if the hazard occurs on a sinuous or a fast road section. Vehicles will hit the obstacle if the drivers do not have sufficient distance to stop their vehicle. The obstacle appears in the middle of the hazardous area at the simulation beginning.

3.3 Numerical setups

Parameters of the simulator have been defined based on data from the literature and on site measurements. Usual settings and traffic parameters were selected based on data from the Vaud canton (2012) and the FEDRO (2012). A regular counting of vehicles on the road provides precise data of the traffic classes (vehicles types) running on the section and gives hourly variations of the flux. The average traffic is defined as 350 vehicles per hour corresponding to the average daily traffic (ADT). The length of cars was determined from average lengths obtained from internet websites of car manufacturers (4.5 m). The length chosen for trucks (12 m) is an approximation of the length of the majority of trucks observed during the field measurements although much longer road trains were observed.

Speed and visibility variables are based on field observations. They differ according to the road sections. In Switzerland, the speed limit on roads outside localities is 80 km h^{-1}. Around temporary traffic lights site construction, the limit is reduced to 60 km h^{-1} on the studied road. The speed reductions in curves were calibrated on observed speeds in curves. Achieved truck speed was set to 40 km h^{-1}, speed they rarely exceed on a mountain road. Visibility distances also come from field observations. Truck drivers have a better visibility as car drivers because of their higher position above the road.

Distance limits before the vehicles brakes are estimated from field observations by estimating the minimum distance before a vehicle brakes. They adapt their speed regarding the lower speed of the previous vehicle or stopping in front of an obstacle. These parameters were chosen in coherence with field observations and maintained constant for the different simulations. Thus, it was possible to compare the scenarios and the different road segments. Some parameters of the simulations are presented in Table 3.

4 Results

It is necessary to mention that the results differ greatly regarding the input parameters of the simulation. The number of vehicles per hour and the average speed are parameters that influence directly the static and dynamic risk, as well as delimitation of the dangerous zone. To assess the risk on a real section, field observations and measured parameters should be taken as inputs for the simulation. The simulator calculates results for each lane. The two risk results, for lane 1 and 2, are averaged in this paper into one value for each scenario.

The results of three of the eight sections of the cantonal road Aigle – Col du Pillon that were analyzed are presented below (Figs. 6 and 7) (Table 4). Moving the area before or after a turn can completely change the outcome of risk. For example, in the case of dense traffic, vehicles before a tight turn will slow sharply but go faster once they have passed. If the hazardous area begins a few tens of meters before the turn, the result of the dynamic risk will be very different with a calculation which takes into account only vehicles that have passed the turn and drive faster.

In the three examples, the results demonstrate that the risk can be increased by over 300 % compared to results of static risk calculation in the case of vehicles blocked behind an obstacle (scenario 3). This increase is slightly lower for road sections with an alternating traffic (scenario 2) because vehicles do not indefinitely remain in the hazardous zone. The dynamic traffic simulator clearly shows an increase of the risk induced by obstacles presence on the road (traffic lights placed into the dangerous area, rocks, etc.) (Fig. 6).

5 Discussion

5.1 Comparison between static and dynamic methodologies

Results have to be carefully analyzed to compare the static with the dynamic risk assessment methods. For the free road (scenario 1) the dynamic risk can be up to 50 % higher than the static risk on the same road section. For Col du Pillon section, the road is a long straight line and vehicles drive at the speed limit, meaning that the vehicles are not slowed by the roads configuration but only by a potential slow moving vehicle which would slow down the traffic and may form a column. In this case, the dynamic risk is only 7 % higher than the static one. For the Pont-Bourquin section, the dynamic risk is 27 % higher than the static one. In this case we observe that the speed limit defined in the simulator at 50 km h^{-1} is too high because the average speed calculated by the simulator in the big turn is around 35–40 km h^{-1}. This difference results in a prolonged presence of vehicles in the risk area and therefore increases the risk. The dynamic risk in Fontanney section is 53 % higher compared to the usual static methodology. This important increase is due to the high sinuosity of the road. The vehicles speed in the hair pin bend is very low, around 10–20 km h^{-1} (Fig. 8), generating long presence in the hazardous area.

For the second scenario, with traffic lights, we observed an increase in risk of 133 % for the Fontanney section compared to the static risk calculation. It is explained by the fact that the vehicles are stopped by the traffic lights located in the hazardous zone. Positions of the hazardous zone and traffic lights defined in the simulation generate vehicle columns of 75 m inside the hazardous area for both traffic lights. This immobilization of vehicles in this area causes the risk increase. Pont-Bourquin section simulations show very different results. The risk is reduced by 48 % compared to static results because the vehicles wait outside the hazardous area. In the case of Col du Pillon, the cars are stopped in a potential hazardous zone because of repairs works due to a doline. In this case, vehicles stopped by the traffic light form a column of 45 m in the risk area and in both directions. Like in Fontanney section, the risk increase (153 %) between static and dynamic risk is important due to the important number of vehicles.

For the last scenario with an obstacle cutting the road, it can be observed that the risk increases between 150 and 350 % compared to the static method. The vehicles exposure on short sections in the static calculation is lower as in long sections. Thus, taking into account stopped vehicles or vehicles in the traffic jam within the hazardous area (scenario 3, Fig. 5), leads to the fact that the risk differences between the static and dynamic risk calculation is higher on short sections than on long sections (Table 4).

In the case of the section of the Col du Pillon, vehicles drive fast (80 km h^{-1}) and the hazardous zone is short, which leads to an increase of 333 % compared to static risk (because the static risk is very low). Speeds in Fontanney and Pont-Bourquin areas are lower and the lengths of the sections are longer, explaining why the relative risk increases are lower than at Col du Pillon. Dynamic risks differences between Fontanney and Pont-Bourquin sections can be explained by different sinuosities reducing vehicles speeds in turns.

5.2 Advantages and limitations of the dynamic approach

The main advantage of the dynamic approach for risk calculation on roads is a better representation of real traffic regarding the interaction between different vehicles. If the traffic on the motorway can be assimilated to a stream composed of vehicles (Treiber, 2010), the traffic on mountain roads strongly depends on interactions between vehicles. This is why the dynamic approach is particularly well suited to winding and/or steep roads, as it is not based on an average vehicle behavior.

The present version could be improved by developing 3-D model (to integrate road slope and 3-D visibility based on the DEM). Looking forward, we could imagine introduce the code as an applet in a GIS.

5.3 Recommendations

Despite the simplicity of the model, it highlights some measures that can help for risk reduction. For instance, it shows the importance to optimize the position of traffic lights relatively to hazardous areas, otherwise the risk can easily be multiplied by a factor of two. Speed in hazardous areas must be defined to fluidize traffic as much as possible to avoid that vehicles pass through the section with a reduced speed, which increases the probability to be hit by a natural hazard. Speed on sinuous sections should be chosen to minimize the risk of accidents between vehicles or between a vehicle and a natural hazard because the result of an accident is the stopping of vehicles, which increases drastically the exposition to hazard.

Practically, it is difficult to reduce the risk only by signalization. Field observations have shown that the speed is often not respected on mountain roads. Local drivers who know well the road often drive much faster than the limitations. It may be easier to take protective measures such as nets, dams, anchors, etc. Then, the dynamic traffic

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

simulator may help to locate critical areas in terms of traffic. It can be used as a tool to support decision making for the construction of mitigation measures.

6 Conclusions

This new approach for risk assessment on roads with dynamic traffic parameters allows being slightly more realistic than common methodologies using only static values. As vehicles interactions on mountain roads are important, the integration of these interactions in the model significantly changes the risk estimations. For example, a slow vehicle may generate a vehicle column on a sinuous road and the dynamic approach can model this traffic situation and its impact on the final risk.

The traffic simulator on mountain roads developed for this new risk calculation is a simplified kinematic model of a real traffic situation. Even if it can be improved, this first version gives satisfying results regarding the dynamic risk. The simulator highlights the limitations of static risk calculation on winding roads where vehicles move slower than the speed limit or in scenarios with obstacles on the road or traffic lights. Simulations have only required some on-site measurements for calibration with realistic data (e.g. speed). In the future, we can expect that such simulators will provide a simple but effective tool to better assess the risk in relation with traffic and to help them to take decisions for risk reduction on roads.

Appendix A

Pseudocode of vehicules behaviour

Vehicle behavior in relation to the visibility criteria

```
 for every vehicle present on the lane
```

```
  find curvature associated with visibility at vehicle
position

   if limit 1 < curvature < limit 2

    if vehicle speed > desired speed with current curvature

     use small deceleration rate

     if speed < 0

       set speed to 0

    if vehicle speed < desired speed with current curvature
&& no accident

     use acceleration rate

   else if curvature > limit 2

    if vehicle speed > desired speed with current curvature

     use brake deceleration rate

     if speed < 0

      set speed to 0
```

```
      if vehicle speed < desired speed with current curvature && no accident
        use acceleration rate
  else
      if vehicle speed < desired speed && no accident
        use acceleration rate
end
```

Vehicle behavior in relation to an obstacle

```
for every vehicle present on the lane
  find distance between vehicle and obstacle
  if distance < length of vehicle
    display accident
    set speed to 0
  else if distance < visibility
```

```
        use brake deceleration rate
        if speed < 0
          set speed to 0
end
```

Vehicle behavior in relation to other vehicles

```
for every vehicle present on the lane after the first one
  calculate distance to precedent vehicle
  if distance < length of vehicle
    display accident
    set speed to 0 for both vehicles
    disable possibility to accelerate
  else if distance < security distance && speed > speed of preceding vehicle
    use brake deceleration rate
```

```
      if speed < 0
        set speed to 0
      else if distance < visibility distance && speed > speed of preceding vehicle
          use small deceleration rate
          if speed < 0
            set speed to 0
else if distance < visibility distance && speed < speed of preceding vehicle
          use acceleration rate
  end
```

Vehicle behavior in relation to traffic lights

```
  for every vehicle present on the lane after the first one
    calculate distance to traffic light
    if traffic light is red
```

```
      if distance < visibility && traffic light is ahead &&

          use brake deceleration rate

      else if traffic light is green

        if vehicle speed = 0 && no accident

          use acceleration rate

        else if vehicle speed > 0 && speed < speed of preceding
vehicle && no accident
use acceleration rate

  end
```

Note that each vehicle can only accelerate, decelerate or brake once during a time step.

Vehicle speed is always controlled so that it cannot become negative.

Acknowledgements. A grateful thanks to Céline Longchamp for the precious help for and the constructive remarks to improve the quality of the manuscript.

References

Baillifard, F., Jaboyedoff, M., and Sartori, M.: Rockfall hazard mapping along a mountainous road in Switzerland using a GIS-based parameter rating approach, Nat. Hazards Earth Syst. Sci., 3, 435–442, doi:10.5194/nhess-3-435-2003, 2003.

Borter, P.: Risikoanalyse bei gravitativen Naturgefahren: Methode, Bundesamt für Umwelt, Wald und Landschaft, 115 pp., available at: http://www.planat.ch/, 1999.

Bründl, M.: Guide du concept du risque, Plateforme nationale “Dangers Naturels” PLANAT,61 pp., available at: http://www.planat.ch/, 2009.

Budetta, P.: Assessment of rockfall risk along roads, Nat. Hazards Earth Syst. Sci., 4, 71–81, doi:10.5194/nhess-4-71-2004, 2004.

Bunce, C. M., Cruden, D. M., and Morgenstern, N. R.: Assessment of the hazard from rock fall on a highways, Canadian Geotech. J., 24, 344–356, 1997.

Cajos, J., Trocmé-Maillard, M., Huber, M., Arnold, P., Vollmer, U., Sandri, A., Raetzo, H. Dorren, L., Egli, T., Eberli, J., Knuchel, R., Kienholz, H., Donzel, M., Utelli, H. H., and Perren, B.: Risk concept for natural hazards on national roads, Federal Roads Office, 108 pp., available at: http://www.astra.admin.ch/, 2009.

Canton de Vaud: Trafic journalier moyen (TJM), available at: http://www.vd.ch/ (last access: 8 November 2012), 2012.

Corominas, J. and Moya, J.: A review of assessing landslide frequency for hazard zoning purposes, Eng. Geol., 102, 193–213, 2008.

Corominas, J., Copons, R., Moya, J., Vilaplana, J., Altimir, J., and Amigó, J.: Quantitative assessment of the residual risk in a rockfall protected area, Landslides, 2, 343–357, 2005.

Dorren, L. K. A.: A review of rockfall mechanics and modelling approaches, Prog. Phys. Geogr., 27, 67–87, 2003.

Dorren, L. K. A.: Rockyfor3D (v4.0) revealed – Transparent description of the complete 3D rockfall model, ecorisQ paper, 28 pp., 2011.

Einstein, H. H.: Special lecture: landslide risk assessment procedure, in: Proceeding, 5th International Symposium on Landslides, Lausanne, edited by: Bonnard, C., Vol. 2, Rothherdam, A. A. Balkema, 1075–1090, 1988.

FEDRO: Comptage suisse automatique de la circulation routière (CSACR), available at: http://www.portal-stat.admin.ch/ (last access: 8 November 2012), 2012.

Fell, R., Ho, K. K. S., Lacasse, S., and Leroi, E.: A framework for landslide risk assessment and management, in: Landslide Risk Management, edited by: Hungr, O., Fell, R., Couture, R. and Eberhardt, E., Proceedings of the International Conference on Landslide Risk Management in Vancouver, Canada, 31 May–3 June 2005, 3–25, 2005.

Guzzetti, F., Reichenbach, P., and Wieczorek, G. F.: Rockfall hazard and risk assessment in the Yosemite Valley, California, USA, Nat. Hazards Earth Syst. Sci., 3, 491–503, doi:10.5194/nhess-3-491-2003, 2003.

Hungr., O., Evans, S. G., and Hazzard, J.: Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia, Canadian Geotech. J., 36, 227–238, 1999.

Jaboyedoff, M. and Labiouse, V.: Technical Note: Preliminary estimation of rockfall runout zones, Nat. Hazards Earth Syst. Sci., 11, 819–828, doi:10.5194/nhess-11-819-2011, 2011.

Jaboyedoff, M., Choffet, M., Derron, M.-H., Horton, P., Loye, A., Longchamp, C., Mazotti, B., Michoud, C., and Pedrazzini, A.: Preliminary slope mass movements susceptibility mapping using DEM and LiDAR DEM, in: Terrigenous Mass Mouvements, edited by: Pradhan, B. and Buchroithner, M., Springer-Verlag Berlin Heidelberg, 109–170, 2012.

Kerner, B. S.: Introduction to Modern Traffic Flow Theory and Control: The Long Road to Three-Phase Traffic Theory, Springer, 265 pp., 2009.

MASSA, Documents de présentation de l'Action 1, Les méthodes: available at: http://massa.geoazur.eu/action1/Doc_present.php (last access: 31 January 2012), 2010.

Michoud, C., Derron, M.-H., Horton, P., Jaboyedoff, M., Baillifard, F.-J., Loye, A., Nicolet, P., Pedrazzini, A., and Queyrel, A.: Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps, Nat. Hazards Earth Syst. Sci., 12, 615–629, doi:10.5194/nhess-12-615-2012, 2012.

Pierson, L. A., Davis, S. A., and Van Vickle, R.: Rockfall Hazard Rating System – Implementation Manual, Federal Highway Administration (FHWA), Report FHWA-OR-EG-90–01, FHWA, US Dep. of Transp., 1990.

Roberds, W.: Estimating temporal and spatial variability and vulnerability, in: Landslide Risk Management, edited by: Hungr, O., Fell, R., Couture, R., and Eberhardt, E., Proceedings of the International Conference on Landslide Risk Management in Vancouver, Canada, 31 May–3 June 2005, 129–157, 2005.

Schönhof, M., and Helbing, D.: Criticism of three-phase traffic theory, Transportation Res. Part B, 43, 784–797, 2009.

Treiber, M. and Kesting, A.: Verkehrsdynamik und –simulation, Springer, 368 pp., 2010.

Wilhelm, C.: Wirtschaftlichkeit im Lawinenschutz, Methodik und Erhebungen zur Beurteilung von Schutzmassnahmen mittels quantitativer Risikoanalyse und ökonomischer Bewertung, Eidgenössisches Institut für Schnee- und Lawinenforschung, 1997.

Table 1. Parameters used to assess risk from natural hazards on roads. Bold: output results and input parameters needed to solve kinematics object risk equation. Normal: intermediary parameters solved during the calculation by the simulator. Italic: used only in equations.

Acronym	Complete appellation	Unit
$\boldsymbol{R_{\mathrm{ob}}}$	**Object risk**	**[dead/year]**
$\boldsymbol{R_{\mathrm{ind}}}$	**Individual risk**	**[dead/year]**
$\boldsymbol{F_{\mathrm{e}}}$	**Occurrence frequency of an event**	**[1 yr^{-1}]**
$\boldsymbol{P_{\mathrm{s}}}$	**Damaged proportion of the road [0–1]**	**[–]**
λ	**Death probability when a vehicle is touched [0–1]**	**[–]**
β	**Average vehicle occupation**	**[person]**
$\boldsymbol{t_{\mathrm{sim}}}$	**Simulation time**	**[s]**
t_{cum}	Cumulated time of vehicles observed in the hazardous area during a simulation	[nb vehicles/s]
N_{v}	Number of vehicles exposed in the hazardous area during a given time	[nb vehicle]
l	*Length of the dangerous section*	[*m*]
f	*Conversion factor to convert [km min^{-1}] to [m day^{-1}]*	[–]
v	*Mean speed*	*[km h^{-1}]*

Table 2. Three sections from the studied road Aigle – Col du Pillon, in Vaud canton, Switzerland. The results of this simulation sections are describe bellow. The average speed of vehicles was measured in the field using a pocket traffic radar.

Section	Description	Natural hazard	Average vehicles speed measured in the field [km h^{-1}]
Fontanney	S-track with 2 hair pin bends crossed by a pressure pipe	Debris flows in case of failure of the pressure pipe	45
Pont-Bourquin	Large hair pin bend	Active landslide beside the road	35
Col du Pillon	Straight line	Doline	85

Table 3. Parameters for the simulations.

Parameter	Unit	Section		
		Fontanney	Pont-Bourquin	Pillon
Section length	[m]	1000	600	500
Hazardous area position	[m]	400–600	250–430	200–300
Hazardous area length	[m]	200	180	100
Traffic lights position	[m]	475 and 525	250 and 430	240 and 260
Obstacle position	[m]	500	330	220
Authorized vehicles speed	[km h^{-1}]	50	50	80
Traffic density	[vehicle/hour]	350	350	350
Occurrence of the hazard	[1 yr^{-1}]	20	20	20

Table 4. Dynamic risk results of three scenarios on the road sections and static results of those sections.

Section	Static risk [dead/year]	Dynamic risk [dead/year]		
		Scenario 1	Scenario 2	Scenario 3
Fontanney	0.140	0.215	0.325	0.515
Pont-Bourquin	0.126	0.161	0.078	0.331
Pillon	0.044	0.047	0.112	0.192

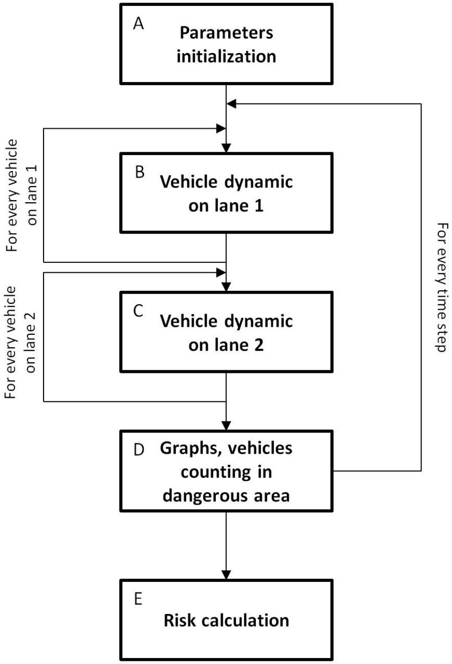

Fig. 1. Structure of the traffic simulator model. Box A is read once at the simulation to initialize the parameters and the first vehicles on the road. The boxes B and C belong to the temporal loop which increments time every time step. During one time unit (1 s), all the vehicles positions on lane 1 (box B) and on lane 2 (box C) are calculated. Finally, after the traffic simulation, different factors related to the risk calculation are computed in boxes D and E.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Simulations parameters

Simulation time	2	[min]
Number of simulation	1	[-]

Obstacle parameters

Time obstacle appearence	300	[s]
Obstacle position from road beggining	500	[m]
Obstacle position variation	0	[m]

Lights location

1st light, from road axis start	450	[m]
2nd light, from road axis start	550	[m]

Authorised speed and speed variation

Authorised speed one lane 1	50	[km/h]
Authorised speed one lane 2	50	[km/h]
Speed variation on lane 1	0	[km/h]
Speed variation on lane 2	0	[km/h]
Trucks speed on lane 1	40	[km/h]
Trucks speed on lane 2	40	[km/h]

Speeds in curve

1st curve limit for speed reduction	0.01	[°]
2nd curve limit for speed reduction	0.05	[°]
Speed reduction for low curve limit	10	%
Speed reduction for high curve limit	50	%

Visibility parameters

Visibility deep for car	30	[m]
Visibility deep for truck	50	[m]
Visibility reduction for low curve	10	%
Visibility reduction for high curve	50	%

Limit distance bevore braking

Car limit dist. before breaking, lane 1	30	[m]
Car limit dist. before breaking, lane 2	20	[m]
Truck limit dist. before breaking, lane 1	30	[m]
Truck limit dist. before breaking, lane 2	50	[m]

Acceleration

Car acceleration on lane 1	0.73	[m/s^2]
Car acceleration on lane 2	0.73	[m/s^2]
Truck acceleration on lane 1	0.43	[m/s^2]
Truck acceleration on lane 2	0.43	[m/s^2]

Deceleration

Car desired deceleration on lane 1	1.67	[m/s^2]
Car desired deceleration on lane 2	1.67	[m/s^2]
Truck desired deceleration on lane 1	1.4	[m/s^2]
Truck desired deceleration on lane 2	1.4	[m/s^2]

Braking

Car breaking on lane 1	7	[m/s^2]
Car breaking on lane 2	7	[m/s^2]
Truck breaking on lane 1	3	[m/s^2]
Truck breaking on lane 2	3	[m/s^2]

Number of vehicles and accidents in risk area

Nb. of veh. in risk area during sim., lane 1	5.6639	[veh.]
Nb. of veh. in risk area during sim., lane 2	4.8372	[veh.]
Nb. of veh. in risk area per day, lane 1	5586.345	[veh.]
Nb. of veh. in risk area per day, lane 2	47710216	[veh.]
Average number of accidents on lane 1	0	[-]
Average number of accidents on lane 2	0	[-]

Lane 1

1 2 3 4 5

Lane 2

1 2 3 4 5

Traffic parameters

Aver. hourly traffic, lane 1	350	[veh/h]
Aver. hourly traffic, lane 2	350	[veh/h]
Amount of tucks, lane 1	10	%
Amount of tucks, lane 2	10	%

Vehicle length

Car length	4.5	[m]
Truck length	12	[m]

Risk parameters

Rt	20	[year]
Ps	1	[/y]
Xperday	2	[/d]
Lamda	1	[-]
Beta	2	[pers.]

Hazardous area

Beggining from road start	450	[m]
End from road start	550	[m]

Risk results

	Dynamic risk	*Static risk*	
Object risk on lane 1	0.047945	0.07	[dead / year]
Object risk on lane 2	0.051518	0.07	[dead / year]
Total object risk	0.099463	0.14	[dead / year]
Individual risk on lane 1	8.5826e-006	8.3333e-006	[dead / year]
Individual risk on lane 2	8.6726e-006	8.3333e-006	[dead / year]
Total individual risk	1.72252-005	1.6667e-005	[dead / year]

Subtraction between static and dynamic risk

Objet risk		
Dynamic - static, lane 1	-0.022055	[dead / year]
Dynamic - static, lane 2	-0.018482	[dead / year]
Tota dynamic - total static	0.013923	[dead / year]
Individual risk		
Dynamic - static, lane 1	2.4924e-007	[dead / year]
Dynamic - static, lane 2	3.3393e-007	[dead / year]
Total dynamic - total static	5.8317e-007	[dead / year]

Fig. 2. Graphic user interface (GUI) of the dynamic traffic simulator in MATLAB®. The GUI is divide into seven boxes: (1) imulation and road management importation of a road section to choose scenario type and to define traffic lights and obstacle location as well as simulation time; (2) speed and visibility parameters, introduction of the different parameters of vehicles kinematics (acceleration, breaking), speed limit and speed reduction in curve linked with visibility parameters; (3) general traffic parameters and vehicles lengths; (4) start and end of the hazardous area location and static parameters used for the risk equation; (5) results of the simulation appear here with vehicles number in the hazardous area, accidents number and dynamic and static risk results and comparison; (6) vehicles identifiers to be plotted in the speed graphic; (7) graph of the road section, the dangerous area, traffic lights and obstacle locations and vehicles displacement.

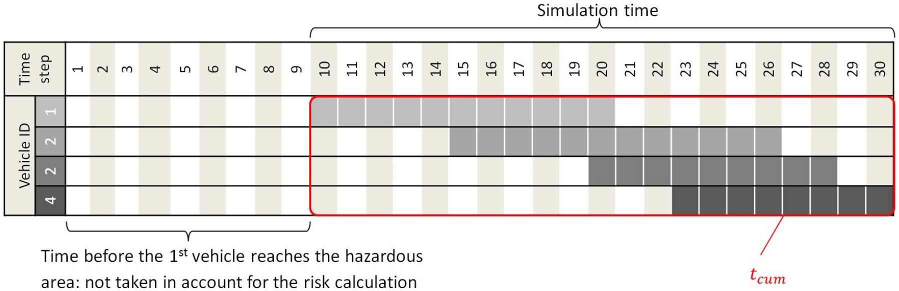

Fig. 3. Cumulated time of vehicles observed in the hazardous area during one simulation. In this example, four vehicles passed through the hazardous area with a total of 38 time steps of cumulated time. Here, one time step is equal to one second. During the first 9 s of the simulation, no vehicle has reached the hazardous area. Thus, time required by the first vehicle to reach the dangerous zone is not included in the simulation duration.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

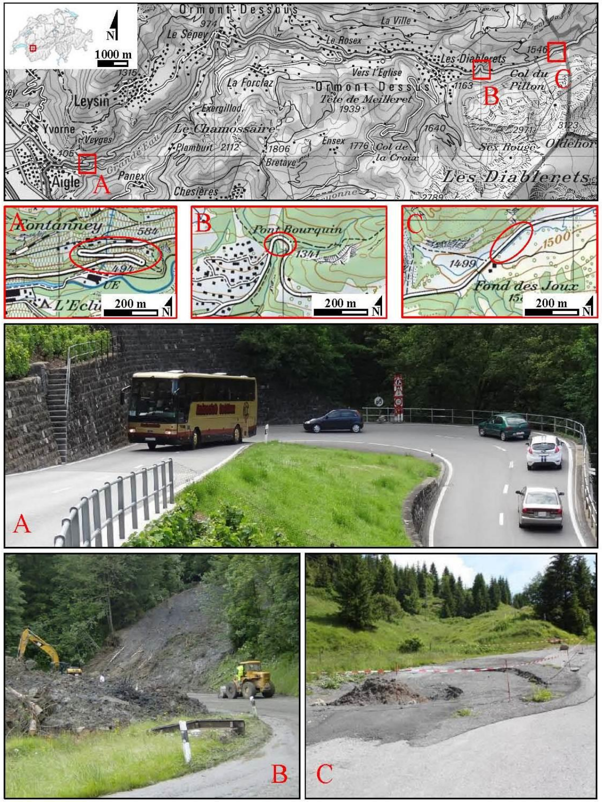

Fig. 4. Location of the three sections on the study road Aigle – Col du Pillon, in Vaud canton, Switzerland. **(A)** Fontanney section with debris flows hazard. The picture shows the south hair pin bend with road works traffic signs and different types of vehicles (2012). **(B)** Pont-Bourquin section threatened by an active landslide (picture of the 2007 event). **(C)** Col du Pillon section with doline hazard (picture of the 2009 event). (Copyright for topographical maps: Swisstopo).

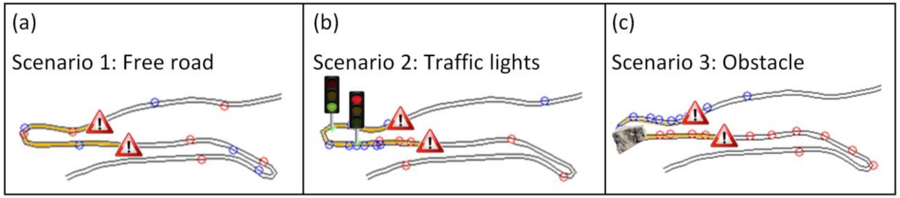

Fig. 5. Illustration of the three scenarios on the Fontanney section. The cautions panels indicate the beginning and the end of the hazardous area (in yellow). Vehicles are represented by circles, red for the lane 1 (uphill) and blue for the lane 2 (downhill). **(a)**: road without obstacles or traffic limitations. **(b)**: traffic regulated by traffic lights. **(c)**: rockfall on the road cutting the traffic and generating vehicles columns on both lanes.

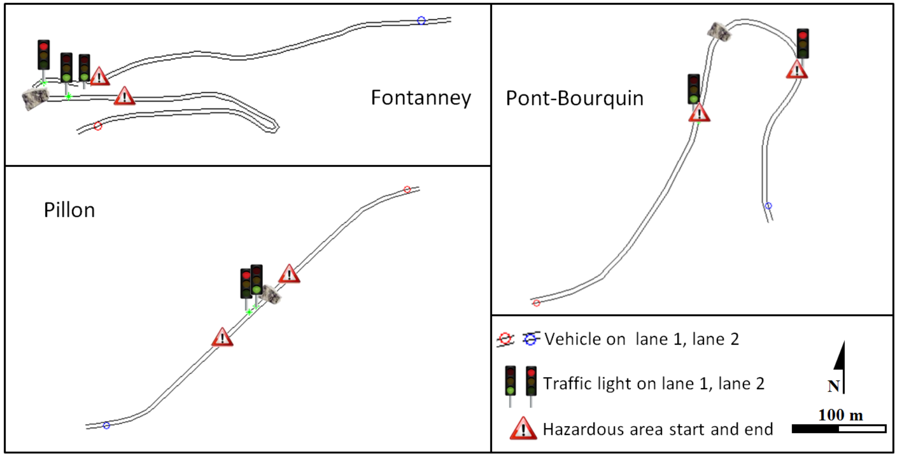

Fig. 6. Sections plans during simulations showing determinant elements configuration.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

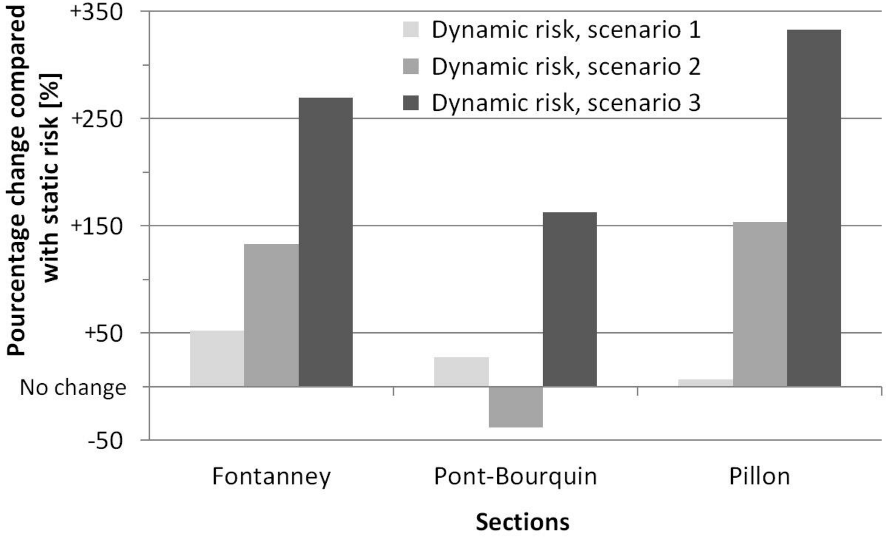

Fig. 7. Calculated dynamic risks normalized to static risk for the 3 scenarios (Fig. 5). Scenario 1: free road; scenario 2: traffic lights; scenario 3: obstacle on the road. A 50 % value for Fontanney section with scenario 1 means that the free road dynamic risk for this section is nearly 1.5 times higher than the static risk on the same section.

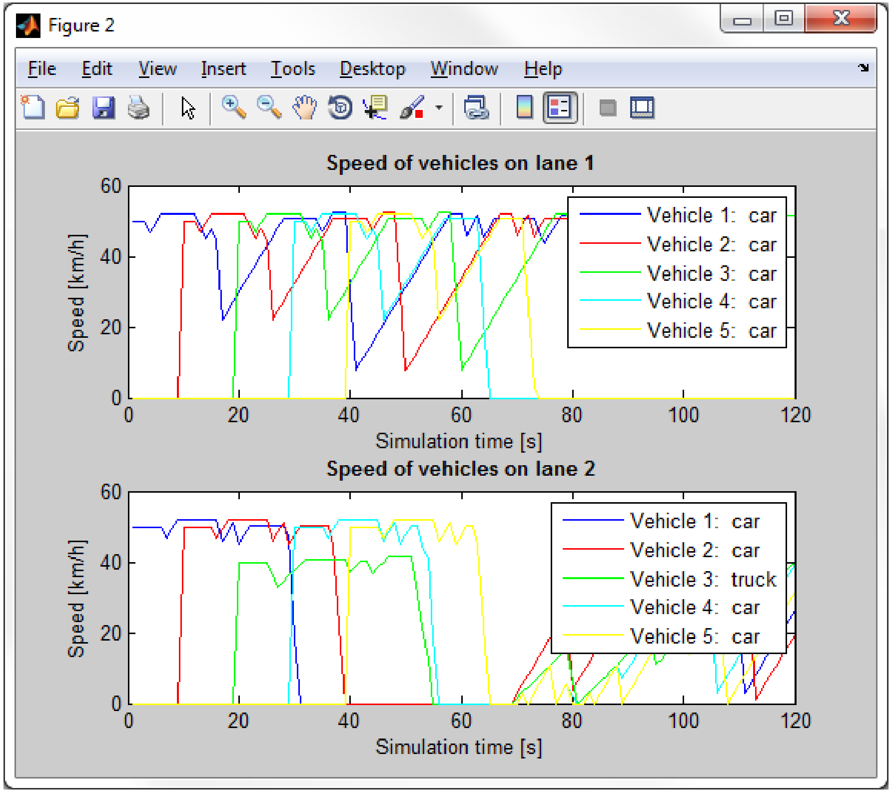

Fig. 8. Speeds plots of the first five vehicles of the simulation on the Fontanney section. We observe the two huge brakes on the lane 1 because of the two hair pin bends. The vehicles on lane 2 are stopped on the red lights before the first hair pin bend during about 30 s.