Probabilistic model for resilience assessment of the Belgian road network

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ABSTRACT: The resilience of an infrastructural network is the network's ability to redistribute traffic when some system members fail. The malfunction could be due, for example, to the collapse of a bridge (total interruption of a network branch) or the opening of a maintenance site (partial cessation of the traffic). In this paper, the resilience of Belgium's leading road network will be discussed, supposing that the interruption of some of its branches happens. The modelling, based on the graph theory, involves regional and national roads and highways. On the graph, the most important Belgian towns were arranged. Through statistical data on inhabitants and on distance between the towns, a probabilistic modelling of traffic flow was developed. An improvement of the modelling was possible thanks to the data on the real traffic flow directly collected by administrations. Following that, a traffic simulation algorithm with a static path assignment was created in MATLAB environment. Through the algorithm created it was possible to simulate the movement of each vehicle within the network. This paper presents the assumed modelling hypotheses and the results in terms of resilience (time lost in traffic, increase in kilometres travelled) when some branches of the E42 highway (Tournai - Liège) must be closed to traffic.

This paper is dedicated to Noemi Basso, a friend and esteemed colleague of Waseda University who recently passed away. A flower too delicate to overcoming the storms of life.

1 INTRODUCTION

Nowadays, human society depends strongly on many systems: the production and distribution of electricity, the production, management and distribution of drinking water, information and communication, banking systems, etc. (Mattsson and Jenelius, 2015).

Over time, these systems become more and more complex with strong internal dependencies between them. This internal dependence can heavily impact on the social life of a whole region If the supply of a service is reduced, or worse, completely interrupted, the systems that depend on that service will operate at a lower level or will stop.

These consequences have led several researchers to realize that some systems are better able to absorb a failure than others: these systems are defined resilient systems.

The concept of resilience was born in the 1950s but it has developed only in the last decade. Born in the field of ecology to describe the resistance of a system to change after a disturbance (MacArthur, 1955; Pimm 1991) the property "resilience" has subsequently found applications in the domain of the economy (Rose, 2009; Rose and Krausmann, 2013), of engineering (Holling, 1996; Bruneau et al. 2003, McDaniels et al. 2013) and lastly in transport engineering (Reggiani, 2013; D'Lima and Medda, 2015).

The resilience of transport infrastructure is a development of resilience in engineering. Transport infrastructure (roads, bridges, tunnels, etc.) is considered part of a system. In this case, resilience can be defined as the ability of infrastructure to move its users to other routes, when there is a reduction in operations (partial or total interruption of a road or a bridge).

For the study of the resilience of a system, there are different approaches. A first classic approach comes from the analysis of the network topology (Xiaodong et al., 2015). In this approach some indicators are used based on the number of nodes, the number of connections and how the nodes are connected to each other. It addresses the vulnerability estimation of the system on the basis of its connectivity properties (Latora and Marchiori, 2005; Dunn, 2016). These methods that follow this first approach are able to analyze any system, require little time for

their implementation, but are inefficient because they cannot capture the specific characteristics of a network compared to another. A second approach developed to analyze the resilience of an infrastructure network is to build operational models and proceed with the simulation of partial or total interruption of the service. The methods that follow this second approach require much more work for their realization but are more effective in the analysis of network behavior. In this research the second approach will be followed.

A simulation is usually done on the basis of real data. However, these data are often difficult to obtain because they require large-scale studies and surveys, both in terms of territory and population. In the case of a transport infrastructure, it is necessary to know how many and which vehicles depart from each node of the network to move to any other node, along which route and with which departure time. Knowing such data on a large infrastructure network, such as the territory of a small country like Belgium, requires a very broad survey or the acquisition and processing of data held by companies that manage applications such as GOOGLE MAPS or WAZE.

In this paper, through the application of the Monte Carlo method, we propose a statistical simulation of the traffic flow, based on the infrastructure network and the importance of the cities connected by the network. This simulation allows to create a traffic model , relatively quickly able to analyze the behavior of the network after a service interruption. Model optimization will be possible if real traffic surveys are available.

2 DEFINITION OF THE TRAFFIC MODEL

Different traffic models are currently available in the literature (Leurent, 2008; Dimon, 2012; Dunn et al. 2013). In general, they can be classified into microscopic models (where the behaviour of each individual vehicle and the interactions between them are described), mesoscopic models (where the behaviour of the vehicles is described on a large scale and the interactions between vehicles are modelled with less detail or not modelled at all), macroscopic models (where the traffic is described on the basis of analogies with other physical models, such as water-flow models).

A second important subdivision of traffic models concerns the modelling of vehicle movement. In this case, it is possible to have static models or dynamic models. In a static model, the individual vehicle is not in motion, but only the path of the vehicle is considered in the model. In a dynamic model, each vehicle has its own speed and its movement on the road network is simulated.

The choice of the model to be used depends on the purpose of the study. A dynamic model allows a much more real traffic modeling with, for example, the possibility to model traffic jams or the possibility to change path during the trip.

Within the dynamic models there is a further subdivision concerning the possibility of a vehicle to change its path once the simulation has started. If there is no possibility of change, the model is defined as static assignment, while it is defined as dynamic assignment otherwise.

In the preliminary study here proposed, a dynamic model with static assignment in mesoscale will be considered.

Since the objective of this study is the analysis and optimization of maintenance choices to be applied to the infrastructures of the Belgian road network, during the progress of the research the choice of the traffic model could be modified.

In a proper infrastructure maintenance plan, social costs (such as the loss of time of users for traffic jams or detour paths, the increase in fuel consumption, the increase in CO_2 spread in the environment, the influences on the economy of the territory) resulting from the total or partial closure of a road for maintenance cannot be excluded.

To be able to consider these social costs, a traffic model capable of performing fast and reliable simulations must be considered in the medium and long-term planning of infrastructure maintenance.

2.1 *Modeling of the Belgian road network*

On the basis of the reasons outlined in the previous section, a first modeling of the Belgian road network was carried out based on the graph theory (Gaihua Fu and Wilkinson, 2013) and a static assignment of the paths. To get the model of the road network, a series of simplifying hypotheses were performed, which can be summarized in the following points:

1. The study focuses only on the most important highways and national roads. The numerical model of the road network is limited to the most important connections to make the simulations faster. The model thus created has 186 knots and 303 branches.
2. The study focuses only on the internal road network. Inbound and outbound traffic is modelled as a boundary condition in the affected nodes.
3. Cities are represented by points positioned in the nodes of the model and ring roads are not modeled (except for the city of Brussels). The model is built to have an overall idea of the behaviour of the road network, the traffic on the ring roads is considered as a local traffic, so it has been excluded from this analysis.
4. Each vehicle makes only one trip, both outward and return. This path is assigned to the vehicle

with a departure time and cannot be changed during the simulation.

5. The default speed of a vehicle is set at the maximum speed that can be reached on a given type of road. This speed may vary depending on the density of vehicles on the road.

The modelling of the road network has been carried out in MATLAB environments, inserting a matrix of incidences of dimensions 186x186 where the coordinate *ij* of the matrix is worth 1 if there is a road connecting node *i* and node *j*, is worth 0 in the opposite case (L'Hoir & Adrien, 2018).

A vector cost of 303 lines was defined. This vector includes on each line the time that a vehicle uses to cover the branch length in a traffic-free state. To determine this time, a speed of 120 km/h on highways, 90 km/h on national roads in Wallonia and 70 km/h on national roads in Flanders were used.

Traffic on the road network is only considered between a certain number of cities. To define this traffic, the 50 most populous cities in Belgium (SPFI, 2018) were placed on the network (Fig. 1).

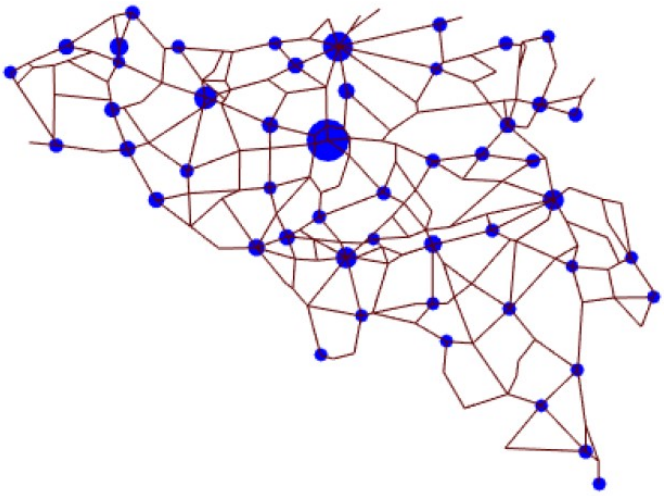


Figure 1. Distribution of Belgium's 50 most populous cities on the road network. The size of the dot is proportional to the number of inhabitants.

2.2 *Probabilistic traffic model formulation*

A probabilistic approach was used to formulate the displacements on the road network, formulating 1600000 pairs between the various cities considered (value equal to the average number of vehicles on the main road network in a day [SPF MT, 2011]). Each city pair is characterized by a city of departure and a city of arrival. The city of departure was chosen randomly based on the number of inhabitants of the cities. The city of arrival was chosen on the basis of the number of inhabitants and on the basis of the distances from the city of departure, weighung this two parameters by means of a coefficient λ assumed as a model variable.

These assumptions derive from the hypothesis that larger cities have more vehicles and that they are also the most important poles of attraction (for trade and work). However, this attractiveness decreases with distance (a person is more inclined to use a service close to him than one far away), which is the reason why both parameters have been considered.

Once the 1600000 pairs had been defined, the Dijkstra algorithm was used to evaluate the routes that the user would choose on the basis of the minimum travel time in optimal traffic conditions.

A departure time and a return time are assigned to these paths, in a probabilistic way, to have on the road network a distribution of hourly traffic similar to the graph in Fig. 2. (Cornelis et al., 2012).

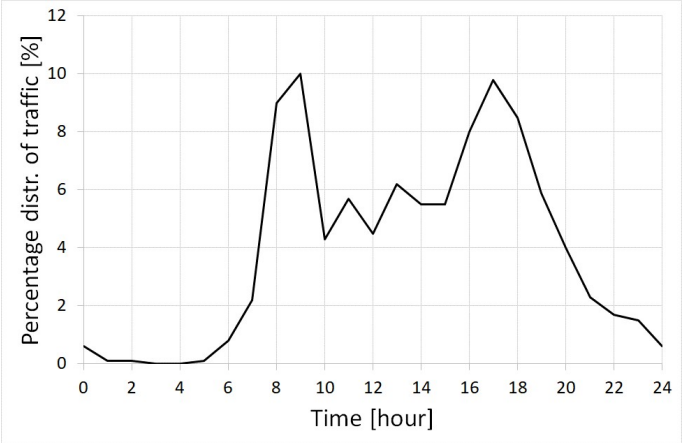


Figure 2. Hourly distribution of displacements of the Belgian population (Cornelis et al., 2012).

The vehicles are then flown on the graph model of the road network in order to obtain a daily traffic simulation.

On the basis of data available from the scientific literature (Chiu et al., 2010; Grabec 2014) a relationship is assigned to each vehicle (Fig. 3) between its speed and the density of the vehicles in the section of road considered.

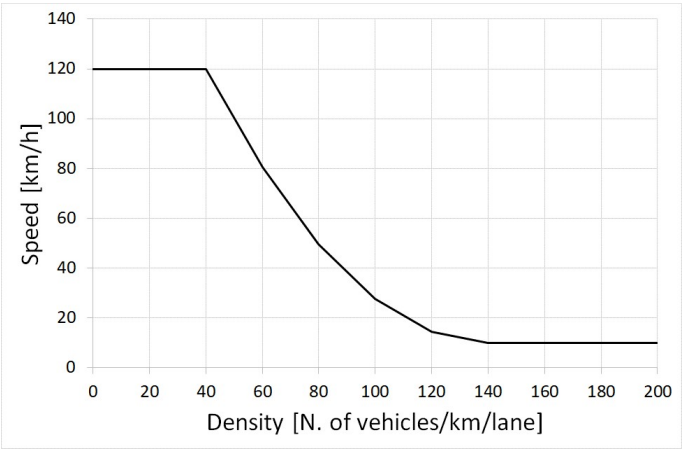


Figure 3. Variation of the average speed of vehicles on a road as a function of the density of vehicles.

The graph in Fig. 3 refers to a road with only one lane per direction of travel; if there are several lanes, the density of vehicles is doubled (two-lane road) or tripled (three-lane road). To use the relationship between speed and density of vehicles, each graph branch has been divided into sections of 100 m in length. This value was decided according to the time step used in the numerical simulation.

The distinction between heavy and light traffic is made on a percentage basis. Of the 1600000 vehicles taken into account, a ratio of 7% of trucks on national roads and 14.5% on highways is considered (Cornelis et al., 2012).

For the traffic incoming and outgoing of the Belgian territory, it is referred to the Figure 4, reproducing the greatest flows of heavy traffic that cross Belgium. (Strale, 2011). Unfortunately, there is no known information on the flows of incoming and outgoing light traffic therefore it will not be taken into account in this analysis.

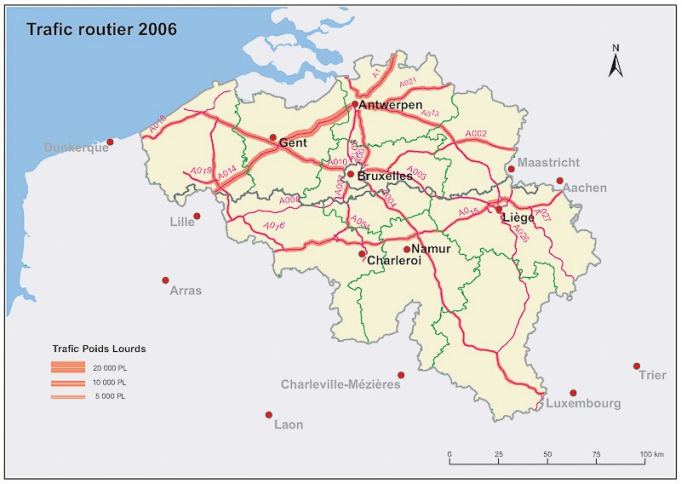


Figure 4. Heavy goods traffic flows in and out of Belgium (Strale, 2011).

3 GENERAL BEHAVIOUR OF THE MODEL

Through the road network modelled with a graph, the paths defined in a probabilistic way, the starting times and the relationship between speed and density, it is possible to perform temporal analyses of traffic flows over a day.

The parameter λ of the probability model (section 2.2) is identified on the basis of an identification process so that the traffic model provides an average distance travelled by all vehicles (heavy traffic excluded) of about 70 km. (Cornelis et al., 2012). Once the parameter λ was determined, the number of vehicle passages in 10 traffic control stations was verified. The Walloon Public Service kindly provided the actual data, obtained with counting sensors.

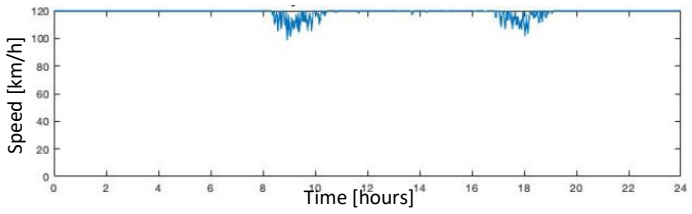
The results of this comparison are shown in Table 1. As you can see, the model (optimized only on the average travel distance) is already able to provide a good approximation of a daily traffic situation.

The model is able to represent the traffic slowdown related to the closure of a lane due, for example, to the presence of a maintenance site on the road.

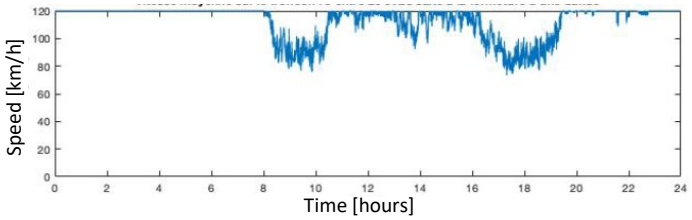
Table 1. Comparison between real data and numerical simulation outcomes.

ID	Actual number of vehicles	Result of the simulation
E411-a	120000	85500
E411-b	30000	20500
E17	81000	55000
E19-a	96000	134500
E19-b	120000	138000
E25	37000	24000
E40	69000	75000
N55	7000	16000
N80	7500	1500
N86	9100	1200

The graphs in Fig. 5 show the effect of closing a lane on average traffic speed. The figure above shows how the average speed (at 120 km/h with low traffic) is slightly reduced from 9 a.m. to 11 a.m. and from 5 p.m. to 7 p.m. (peak traffic periods).



a)



b)

Figure 5. Influence of closing a lane on the average speed of a highway section. (a) average speed before closing. (b) average speed after closing.

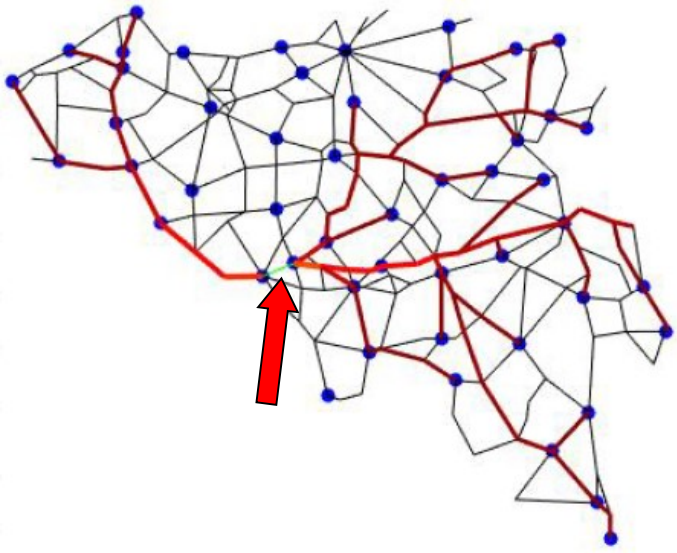
This reduction is much more marked in the graph below in Figure 5, which has been assessed with the same traffic model but considering only 2 lanes available (temporary closure of a lane due to a maintenance site).

4 ANALYSIS OF A MALFUNCTION OF A ROAD

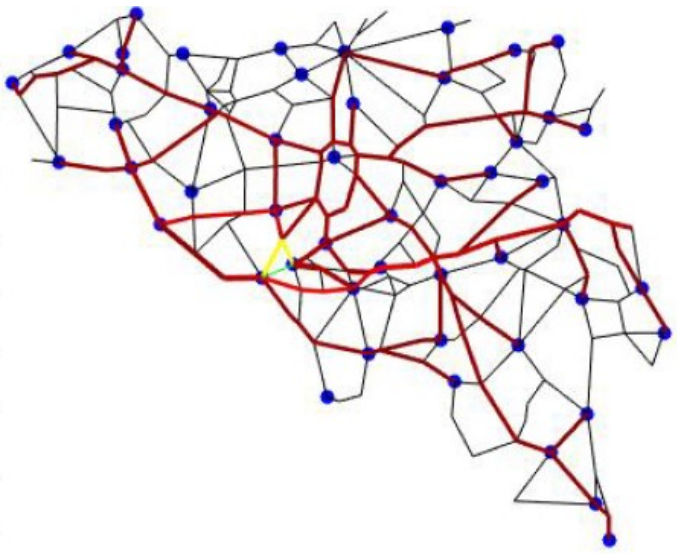
The proposed model is capable of assessing the social impact (hours lost in traffic and the increase in kilometres covered by vehicles) caused by the closure of a section of road. In this research, nine sections of road will be considered on which a total closure will be simulated. This could be the case of the loss of an infrastructure (bridge) along the section of road.

The first simulation carried out concerns the closure of the highway section that connects the city of Mons with La Louviere. This section is part of the E42 highway, one of the most important in Belgium and crosses Belgium horizontally connecting France to Germany.

Figure 6.a shows the position of the affected road section and all paths passing through that section.



a)



b)

Figure 6. Highlighting of all paths that cross the section affected by the malfunction. Before the service malfunction (a) and after the loss of the road (b).

Figure 6.b shows the paths evaluated on the model with the closure of the section concerned. Note that part of the traffic moves to the simplest detour route (in yellow in Figure 6.B where queues are created) but a good part of the vehicles change direction, modifying the traffic conditions even in areas very far from the closed section. This modification increases the traffic on the Brussels ring road (already heavily loaded with vehicles) and causes a very strong increase in the average journey time (from 61 minutes to 149 minutes) for the vehicles concerned. In table 2 the numerical results of the simulation.

Table 2. Numerical outcomes in terms of social impact relating to the closure of the section of highway between Mons and La Louviere.

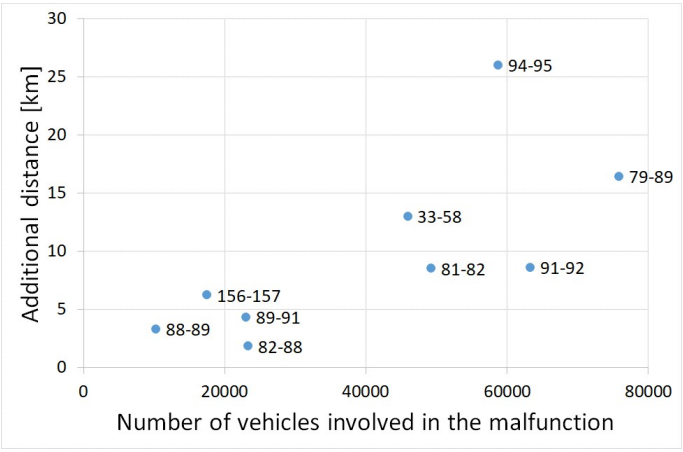
Number of vehicles involved	49345
Number of trucks involved	8229
Average time without malfunction [min]	61
Average time with malfunction [min]	149
Average distance covered without malfunction [km]	94
Average distance covered with the malfunction [km]	103

The above analysis is applied to the 9 sections of the road network listed in Table 3.

Tabele 3. Summary of the road sections on which a malfunction has been simulated.

ID	
81-82	E42 / Mons – La Louvière
82-88	E42 / La Louvière – Chapelle-lez-Herlaimont
88-89	E42 / Chapelle-lez-Herlaimont – Gosselies
89-91	E42 / Gosselies – Fleurus
91-92	E42 / Fleurus – Sombreffe
79-89	E420 / Nivelles – Gosselies
94-95	E411 / Perwez – Louvain-la-Neuve
156-157	E411 / Wellin – Ciney
33-58	E17 / Gand – Lokeren

The graphs in Figure 7 summarise the results in terms of additional kilometres and additional minutes for all analyses performed.



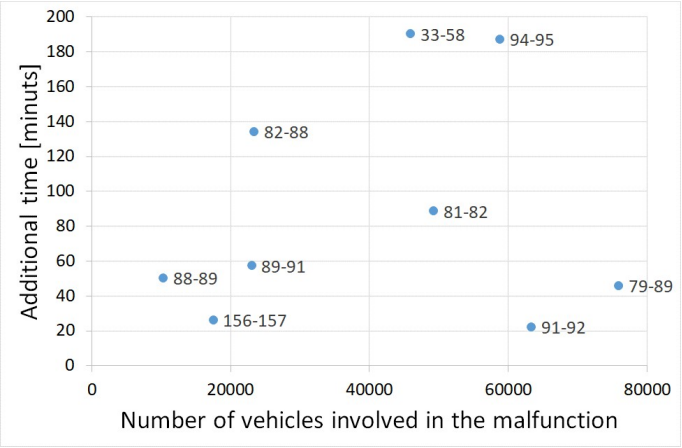


Figure 7. Graphs representing the "strongest" and "weakest" points of the road network (where the increase in kilometres and minutes on the paths is highest) following the simulations performed.

As can be noted from the graphs in Figure 7, the impact on the road network of a possible closure of a section is extremely variable. Even if only the E42 highway is considered, there are sections where a possible loss of functionality causes few problems (Chapelle-lez-Herlaimont - Gosselies) while other sections that are fundamental for the good service of the system (Mons - La Louvière).

5 CONCLUSIONS

The paper contains an initial modelling of traffic on the entire main road network of Belgium.

The traffic flows between the various cities are defined through a probabilistic modeling that takes into account both the size of the cities and the distances between them. The traffic flows have been calibrated on the data of the average length of the paths, available from the Belgian mobility surveys carried out in the years 2000.

The model does not take into account the problems of micro-modelling of vehicle dynamics (acceleration, braking, changing lanes, intersections, etc.) but is able to consider the relationship between the speed of vehicles and the density of the same on the road.

Although it is a simplified modeling, the simulations are already able to identify the road sections where a possible maintenance site, or the loss of an infrastructure, can generate serious inconvenience on the internal traffic.

In this work we considered 9 different disruption scenarios on roads of the same importance (motorways), showing how the impact of a possible loss of functionality can be extremely different depending on the number of vehicles involved and the possibility to convey traffic along other paths.

Further improvements of this study will concern a better definition of the probabilistic modelling of traffic flows (now developed only considering the number of inhabitants and the distances between the various cities) and the possibility of vehicles to change route during the journey (dynamic assignment).

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