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Measuring urban road network vulnerability using graph theory : the case of Montpellier's road network

Working paper

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Abstract

The urban road network provides spatial access to the city through an overlapping hierarchy, ranging from highways to local access streets. This pattern of network organisation has led to an increased propensity to vulnerability, exposing parts of the city to sharp decreases in accessibility when traffic blockages occur on the main links or at junctions. Our aim is to define road network vulnerability and to measure the road network's exposure to risk. We postulate that the network morphology, structure and level of congestion can be influencing factors. Two vulnerability indices which pinpoint accessibility loss in the city by removing links and vertices one by one, have been developed to assess the network's vulnerability.

Keywords

accessibility, graph modelling, Montpellier, risk, urban road network, vulnerability.

Introduction

Vulnerability, exposure to risk or reliability are already well researched concepts in the field of transport (Bell and Lida 1997, Miller and Shaw, 2001). They have been studied not only from a safety point of view, but also as a problem of an insufficient level of service and its spatial implications (Berdica 1998, 2001, Lida 1999, Chen et al., 1999, Taylor 1999). In recent decades, the urban road network has come to provide complete spatial access to the city through an overlapping hierarchy, ranging from highways to local access streets. This pattern of network organisation is responsible for an increased propensity to vulnerability, exposing parts of the city to sharp decreases in accessibility when traffic blockages occur on the main links or at junctions. Therefore, there is a growing need for a new characterisation of the

network propensity to malfunction, as far as its spatial and functional structures are concerned (Berdica 2002). The first part of our paper focuses, as previous research has done (Beom and Chang 2002, Gleyze 2001, 2003), on defining road network vulnerability and measuring of the road network's exposure to risk. In our approach, we postulate that the network morphology, structure and level of congestion can be influencing factors. The second part of the paper is concerned with the construction of two vulnerability indices and testing of one of them, which pinpoint accessibility loss in the city by removing links and vertices one by one and which have been developed to assess the network's vulnerability.

1. Vulnerability of the urban traffic system: definition and indices

Vulnerability has already been defined by some researchers from a broader perspective, including safety. Focusing on network structure vulnerability from a circulatory point of view, we shall use and build on the definition proposed by Berdica (2000, 2001, 2002) and Goodwin (1992). This is that "there is a need for an overall characterisation of road networks, to gain insight into their propensity to malfunction". Our goal is not to quantify the consequences of risks on a given area, but to evaluate the supply side – the routes between nodes on a network and the nodes themselves – more consistently with our theoretical approach to vulnerability. In this case, we have found it more appropriate to describe the performance of the road system (network + level of service) in terms of serviceability (Berdica 2002). Performance is thus defined more accurately by several criteria and not just the ability to go from A to B. Serviceability is thus "the basic ability of a system to deliver you from where you are, to where you want to be, at the time you want to travel (...) that makes the journey worthwhile" (Goodwin, 1992). We shall bear in mind that "vulnerability in the road transportation system is a susceptibility to incidents that can result in considerable reductions in road network serviceability". The incidents may then be more or less predictable, caused voluntarily or involuntarily, by man or nature. Risks such as maintenance closure and roadworks are not considered, because drivers may know of those incidents in advance and postpone or reroute their journeys accordingly. Blockages and congestion should be of a non-recurrent type, due to random, unplanned restrictions to traffic flow.

Vulnerability is a much more relevant concept than reliability (Taylor, 1999) because it is solely "related to the consequences of link failure, irrespective of the probability of failure" (Berdica 2002).

Vulnerability is determined by the absolute severity of an incident and by the relative consequences of its occurrence on a given infrastructure or service (serviceability in the broad sense). For incidents of equal severity, we can define two potential failure locations on the graph:

- the vertices
- the arcs

and three network structural predispositions that can cause the level of serviceability to fluctuate:

- network morphology predispositions

- network quality predispositions
- network crowding predispositions.

1.1 Road network link vulnerability index

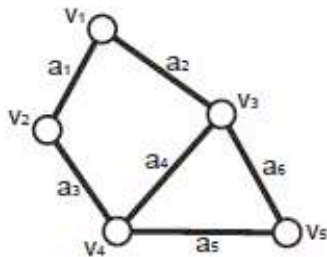
This index measures the loss of overall accessibility recorded by the vertices of a graph representing the modelled area. The arcs are removed one by one to simulate accidental cuts to the links that they represent. Accessibility is considered here to be the sum of the available shortest path between all vertices.

The first stage of the process consists in calculating the sum of the shortest path on the complete network to obtain the reference value. (Figure 1, Stage 1) In Stage 2, the algorithm automatically removes the first arc in the matrix. The sum of the shortest path on the network is thus recalculated for the incomplete network (Figure 1, Stage 2). The resulting sum is at least equal to or greater than the reference value. We then subtract the reference value from this new value to obtain the vulnerability index associated with the removal of that particular arc. The higher the difference between the reference value and the value obtained on the uncomplete graph, the greater the loss of overall accessibility caused by the removal of that arc. The greater the loss of accessibility, the more strategic the link in the network organisation. We then proceed in the same manner for the remaining arcs in the graph, comparing the difference between the reference value of the shortest path and the sum resulting from the removal of each arc (Figure 1, Stages 3 and beyond).

FIGURE 1 – LINK VULNERABILITY

LINK VULNERABILITY

Stage 1: general reference value calculation (complete graph)



n vertices (junctions)

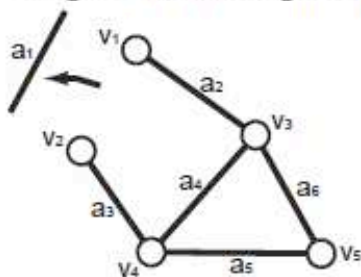
m arcs (links)



$$\alpha = \sum_{i=1}^n \sum_{j=1}^n d(i, j)$$

α : sum of minimal distances $d(i, j)$ between all vertices in kilometres or minutes with or without traffic (m arcs)

Stage 2: a₁ strategic significance calculation



n vertices

m-1 arcs (m-a₁)

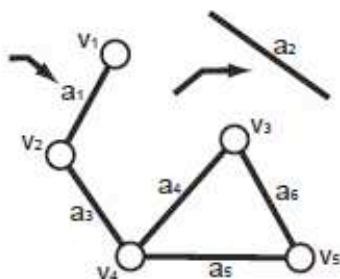
$$\beta(a_1) = \sum_{i=1}^n \sum_{j=1}^n d(i, j)$$

$\beta(a_1)$: sum of minimal distances between all vertices (m-1 arcs)

Vulnerability score: a₁ ← $\beta(a_1) - \alpha$

$\beta(a_1) - \alpha$: decrease in accessibility due to the removal of a₁

Stage 3: a₂ strategic significance calculation



n vertices

m-1 arcs (m-a₂)

$$\beta(a_2) = \sum_{i=1}^n \sum_{j=1}^n d(i, j)$$

$\beta(a_2)$: sum of minimal distances between all vertices (m-1 arcs)

Vulnerability score: a₂ ← $\beta(a_2) - \alpha$

Stage 4: a₃ strategic significance calculation

...

1.2 Road network vertex vulnerability index

This index is based on the same principle as the index measuring arc vulnerability. The purpose of this index is to evaluate the loss of overall accessibility resulting from the removal of each vertex and to hierarchise the vertices according to their strategic importance in the network. Accessibility is calculated in the same way as for the link vulnerability index, based on the shortest paths available on the network. There are some differences, however. Firstly, the removal of a vertex only requires calculating the shortest paths between the other vertices in the graph, even for the reference value calculation. The comparison of accessibility values between complete and

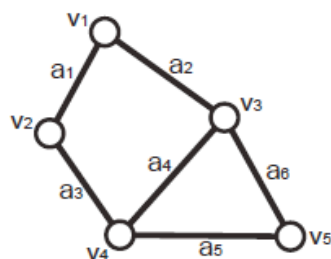
incomplete networks should be done using the same number of vertices. Thus, there is more than one reference value in this index; it changes with each vertex removal (Figure 2, Stages 1 and 3). Furthermore, the removal of a vertex results in the disappearance of all the adjoining arcs (Figure 2, Stage 2), substantially increasing the average loss of accessibility. Technically, the algorithm chooses the first vertex in the matrix (v_1) and calculates the level of accessibility between all the vertices (reference value) through which the shortest paths pass (v_1) (Figure 2, Stage 1). The same calculation is made after the removal of (v_1) (Figure 2, Stage 2). The resulting sum is equal to or greater than the reference value. The vulnerability index associated with the removal of the vertex (v_1) is obtained by subtracting the reference value from it. The higher the score, the longer the diversions on the network due to the paralysis of (v_1) and the higher its strategic role in the network organisation. The strategic importance of the vertices depends on their location, whether central or peripheral, and on the number and types of arcs (morphology, structure and quality) connected to them. We then proceed in the same manner for the remaining vertices in the graph, comparing the difference between the reference value of the shortest path available and the sum resulting from the removal of each vertex (Figure 2, Stages 3 and beyond).

This second index is particularly relevant for measuring what the literature calls "scale-free networks" (Barabasi 2002, Lagues and Lesne, 2003). These new types of networks tend to be more resilient to accidental blockages of several vertices, but conversely are highly vulnerable if incidents occur on specific strategic vertices usually called "super vertices" because of their high level of connectivity. Hub-and-spoke structures are built according to this network logic, in which hubs become highly vulnerable.

FIGURE 2 – JUNCTION VULNERABILITY

JUNCTION VULNERABILITY

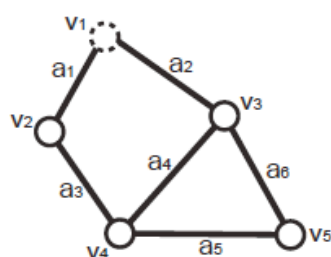
Complete graph



n vertices (junctions)
m arcs (links)



Stage 1: v1 reference value calculation

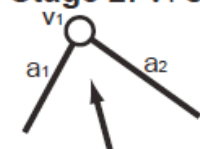


n-1 vertices (n-v1)
m arcs

$$\alpha(v_1) = \sum_{i=1}^{n-1} \sum_{j=1}^{n-1} d(i, j)$$

$\alpha(v_1)$: sum of minimal distances $d(i, j)$ between n-1 vertices in kilometres or minutes with or without traffic (m arcs)

Stage 2: v1 strategic significance calculation

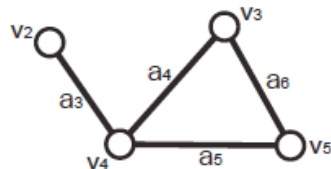


n-1 vertices (n-v1)
p = v1 associated arcs
m-p arcs

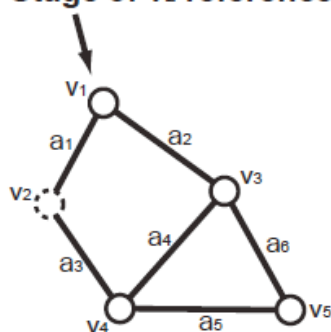
$$\beta(v_1) = \sum_{i=1}^{n-1} \sum_{j=1}^{n-1} d(i, j)$$

$\beta(v_1)$: sum of minimal distances between n-1 vertices (m-p arcs)

Vulnerability score: $v_1 \leftarrow \beta(v_1) - \alpha(v_1)$



Stage 3: v2 reference value calculation



n-1 vertices (n-v2)
m arcs

$$\alpha(v_2) = \sum_{i=1}^{n-1} \sum_{j=1}^{n-1} d(i, j)$$

$\alpha(v_2)$: sum of minimal distances between n-1 vertices (m arcs)

Stage 4: v2 strategic significance calculation

...

The following simulations are based on link vulnerability. Further work is required to model vertex vulnerability. Research on this issue is under way at Montpellier University.

2. Morphological vulnerability

Whether relating to arc or vertex vulnerability, a given network may be predisposed to be unable to cope satisfactorily with incidents. The diagram (figure 3) summarises the various accessibility components or network features. Network accessibility, i.e., the ability to go from A to B in a given time, results from a combination of structural, qualitative and crowding components.

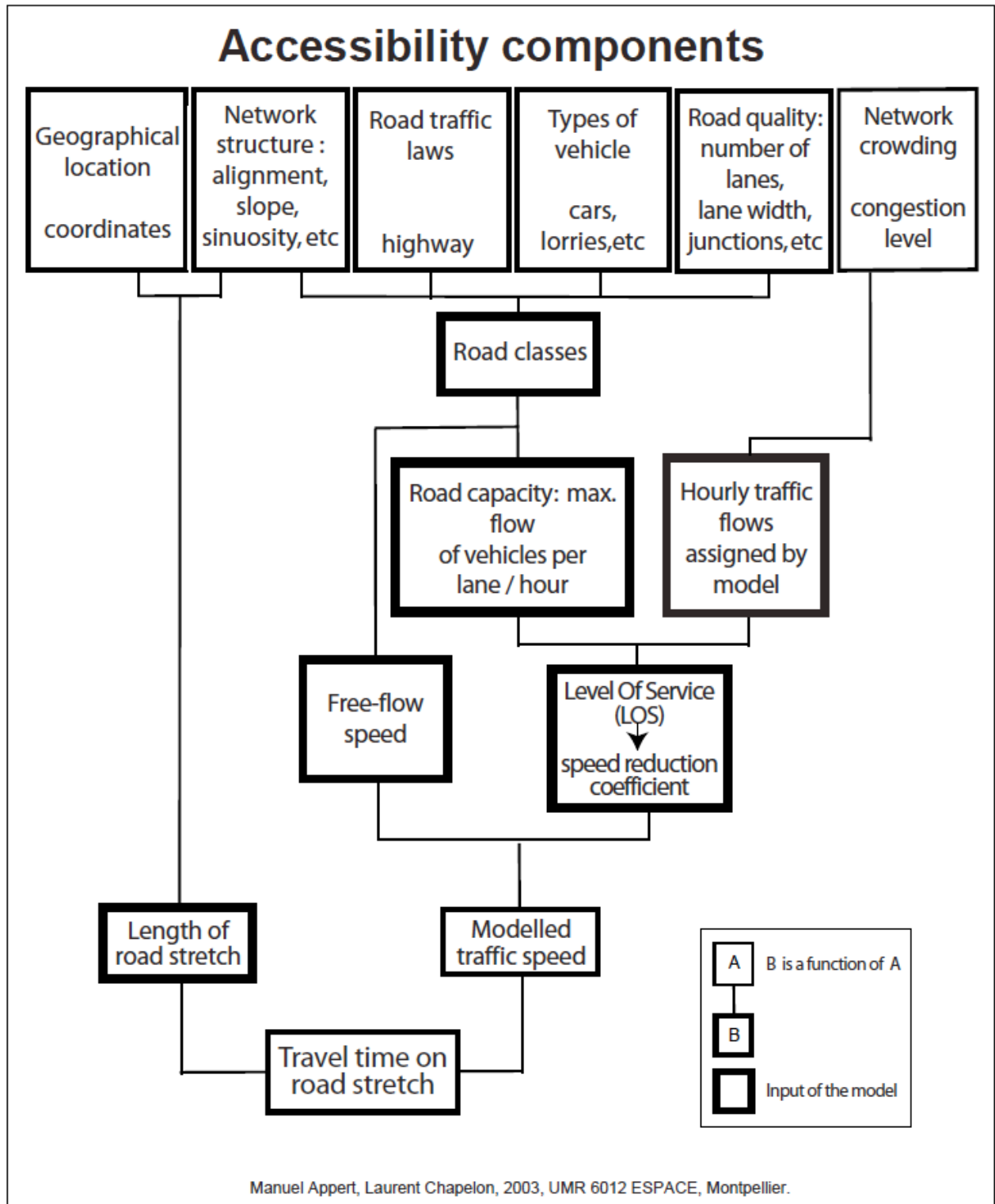
These components can be analysed separately and vulnerability calculations can take only one of the three parameters into account. In the graph valuation process, we characterise each arc in terms of a length value, a qualitative attribute relating to the road class and its level of use or crowding. In this simulation, we only evaluate accessibility with the road length valuation, which measures only the propensity of the network morphology to vulnerability. The road network's morphology is defined by the following criteria:

- number of vertices
- road length for each pair of vertices.

Consequently, we are able to measure the impact of the morphological pattern of the network on the level of vulnerability (all risks being equal).

Before testing the vulnerability indices on the Montpellier urban area road network, a brief summary of the mapping process is necessary to understand how the network is modelled and the results represented.

FIGURE 3 – COMPONENTS OF ACCESSIBILITY



2.1. Mapping vulnerability indices

2.1.1. Graph construction methodology

The graph construction is an important stage in the modelling process because of its potential influence on the results.

There are three main concerns:

- Sticking to the strategic road hierarchy to reflect the local road classification strategy, covering the entire built-up area and distinguishing as accurately as possible between the various types of roads in order to obtain results that are not biased by poor road classification. The resulting graph consists of 302 vertices and 901 arcs (Figure 4).

- In the selection process, the choice of one vertex over another is extremely important. The selection criteria are that the vertices must model all main crossroads (major road intersections) and the junctions where roads change from one type to another. To reduce possible bias, demographic and socio-economic criteria were not used.

- Junction modelling must consider restrictions at some crossroads or interchanges where movement is not allowed in all directions (e.g., restricted access interchanges, no right/left turn, etc.).

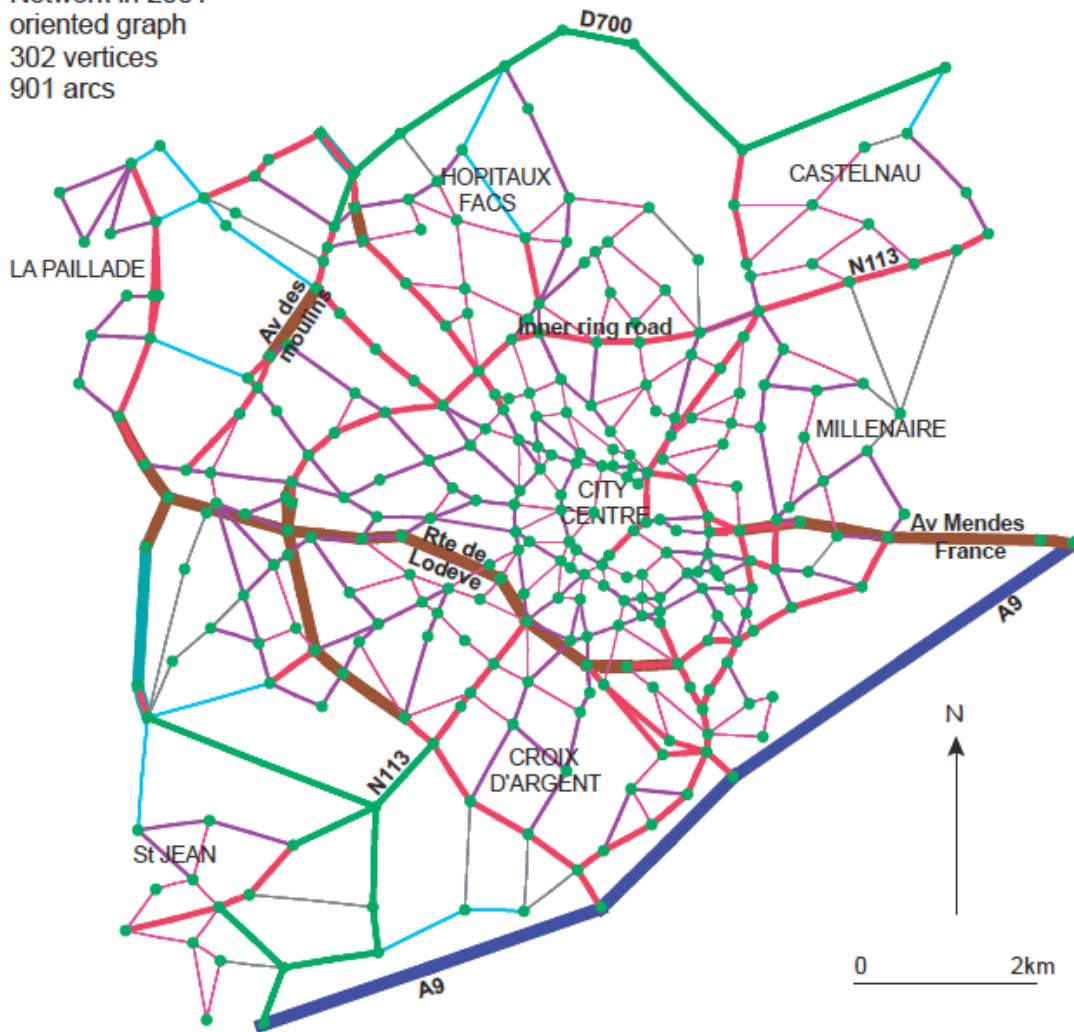
The Montpellier road network model covers the built-up area of the conurbation. The selected area is more homogeneous than, say, the metropolitan region, since population and network density are high almost everywhere. Therefore, results should not be biased by heterogeneity.

The arcs show direction because of our meso-scale approach, which means that one-way streets must be included in traffic movement models.

FIGURE 4 - GRAPH OF MONTPELLIER ROAD NETWORK

GRAPH OF MONTPELLIER URBAN ROAD NETWORK

Network in 2001
 oriented graph
 302 vertices
 901 arcs



Types of roads :

- | | |
|----------------|------------------|
| Motorway | Urban expressway |
| Expressway | Urban artery |
| Trunk road | Urban road |
| Secondary road | Local urban road |
| Local road | |

Area:

CASTELNAU

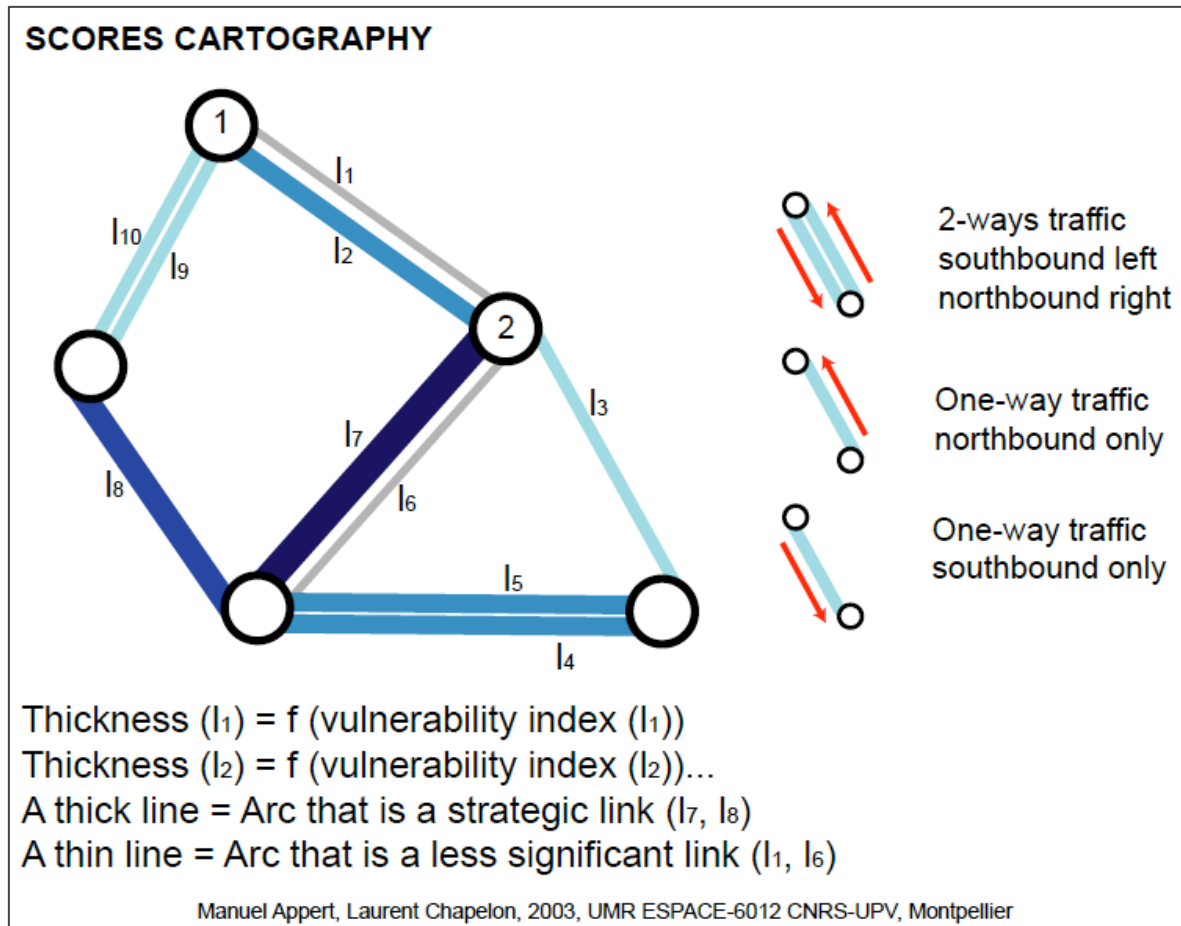
Road:

A9

Manuel Appert, Laurent Chapelon, 2003, UMR 6012 ESPACE, Maison de la Géographie, Montpellier
 NOD and MAP software, A. L'Hostis, L. Chapelon, Ph. Mathis, 1993-2003

Let us take a two-way road with one crossroad at each end (C1 and C2), such as that represented by (I1, I2). To map the arcs, the two traffic directions are separated on either side of Circles 1 and 2 (Figure 5).

FIGURE 5 – MAPPING SCORES



On this two-way link, the northbound arc runs from the right of Circle 2 to the right of Circle 1. The parallel southbound arc runs from the left of Circle 1 to the left of Circle 2.

Only one arc is shown for one-way traffic. The direction of traffic is shown by the position of the arc on the left (northbound) or right (southbound) of the circles.

The description of the network is based on a detailed and comprehensive road classification consisting of nine types of roads, ranging from "local road" to "motorway" (Figure 6). Each road type is characterised by a specific average speed, a free-flow speed (speed attainable in free-flow conditions within legal limits) and a capacity (number and width of lanes, traffic-light density).

FIGURE 6 – ROAD CLASSIFICATION

ROAD CLASSIFICATION - WIDTH	
Road class	road characteristics
Motorway	Dual carriageway major international link with at least 4 3.5m lanes, grade separated junctions and hard shoulder.
Interurban expressway	Interurban dual carriageway with grade separated junctions and at least 4 lanes. part of the strategic road network.
Urban expressway	urban dual carriageway with grade separated junctions. no or reduced hard shoulder (less than 60cm) part of the urban strategic road network.
Trunk road	multilane strategic road with single carriageway and at grade or grade separated junctions (large width 7-9m).
Secondary road	regional link, single carriageway, at grade junctions 2 lane road (medium width 5-7m).
Local road	interurban road of low or medium importance. at grade junctions, 2 lanes totalling less than 5m.
Major urban road	Major urban artery accomodating cross city and cross regional traffic at grade or grade separated junctions, controled intersections.
Boulevard	urban boulevard linking major arteries, providing access to strategic road network mostly at grade and controled junctions.
Local street	local access road, final layer of the urban road hierarchy. uncontroled or controled intersections. Reduced width.

2.1.2. Mapping link vulnerability scores

The results are based only on the arc removal simulations. Further research is under way to model the vertex removal results. The results of each simulation are displayed in three maps: the first to show the impact of the network morphology; the second to show the network quality; and the third to show the impact of the network's functional performance at evening peak hour (5-6 p.m.) with computed speed/flow functions for each type of road.

Mapping the vulnerability indices for each link (Figure 5). The thickness of a link is a function of the vulnerability index calculated. A thick line means that the removal of the arc causes a relatively large loss of accessibility, making the whole network more vulnerable (I7, I8). A thin line means that removal of the does not cause much relative loss of accessibility and exposure to risk is limited (I1, I6).

2.2. Assessment of Montpellier road network vulnerability

2.2.1. The Montpellier urban area and road network (Figure 4) :

Montpellier is the centre of a conurbation with a population of 300,000, located in southern France, between Marseilles and Barcelona. The built-up area has a Roman structure, with a dense city core and sprawling, low-density suburbs. The road network is typical of a French urban area:

- historical roads at the very centre and approaching it, mainly “boulevards” and streets of low to average capacity and geometry.
- some wider roads, built in the latter part of the 20th century to speed up connexions between the central area and the expanding outskirts. Some of these are urban expressways built in a piecemeal approach without any obvious spatial consistency (i.e., Avenue Mendès France, Route de Lodève).
- the city is also bordered by the A9 motorway, a national and international lifeline running along the Mediterranean coast. As the motorway is toll-free in the vicinity of Montpellier, with closely spaced junctions, it is used as a southern west-east bypass.

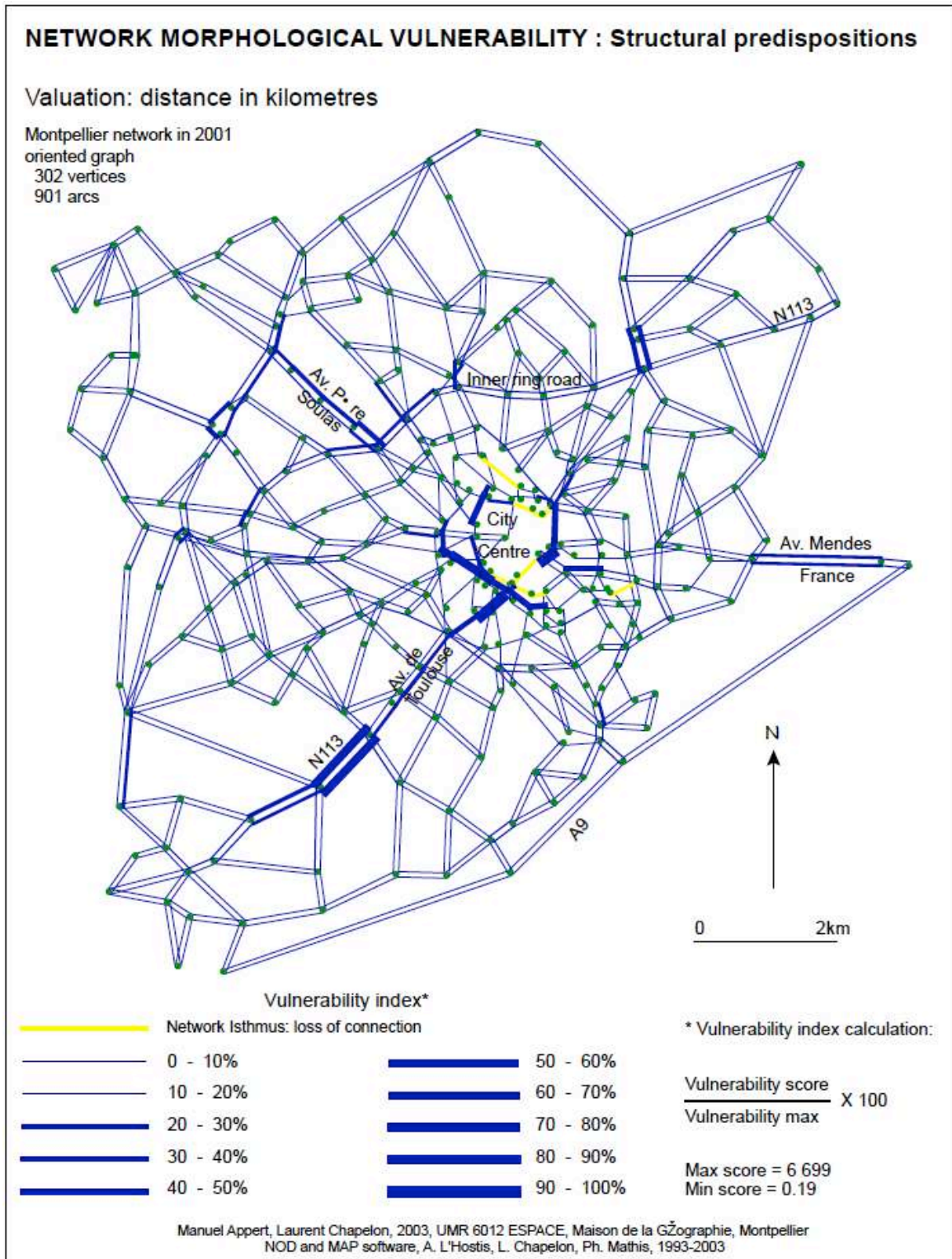
2.2.2. Arc removal simulation

Vulnerability predispositions resulting from network's spatial morphology patterns (Figure 7) :

Our aim is to analyse the performance of one arc compared to that of the other arcs in the scenario, in relative terms. For this purpose, we apply an index from 0% to 100%, divided in 10 classes.

The special yellow class represents network isthmus. These arcs are extremely important because their removal results in a loss of connection. They are one-way streets in succession or boulevards. They include the Tunnel de la Comédie, built in the mid-1980s to allow the pedestrianisation of the main city square. It completes the boulevards boxing in the Ecusson, the historical core of the conurbation.

FIGURE 7 – NETWORK MORPHOLOGICAL VULNERABILITY



The most striking feature is the “natural” predispositions of the city centre. One observes that there are only a few alternatives to the N113, which explains its strategic role, whereas in the centre there are plenty of alternative routes, but these have the highest scores (note, however, the absence of nodes in the very city centre).

The pattern of the routes is clearly radial, converging towards the centre and encircling it with the boulevards. Some cross-routes are obvious, such as those using the inner ring road. The radial network pattern is clearly visible with a convergent series of radials to and from the city centre and an inner ring road connecting them. This translates into a mainly central and radial vulnerability.

3. Network quality vulnerability

Whether relating to arc or vertex vulnerability, a given network may be predisposed to be unable to cope satisfactorily with incidents as we have seen in Section 2. Those components can be analysed separately and vulnerability calculations can take only one parameter into account. In the graph valuation process, we characterise each arc in terms of a length value, a qualitative attribute relating to the road class and its level of use or crowding. In this second case, we evaluate accessibility by adding the free-flow speed valuation, which is the maximum attainable speed given legal limits and road characteristics. We thus measure the propensity of the network quality to vulnerability and the impact of a typical circum-radial hierarchised network structure. We define the network's quality by:

- the number of vertices, and
- the free-flow speed on links between pairs of vertices (Figure 6).

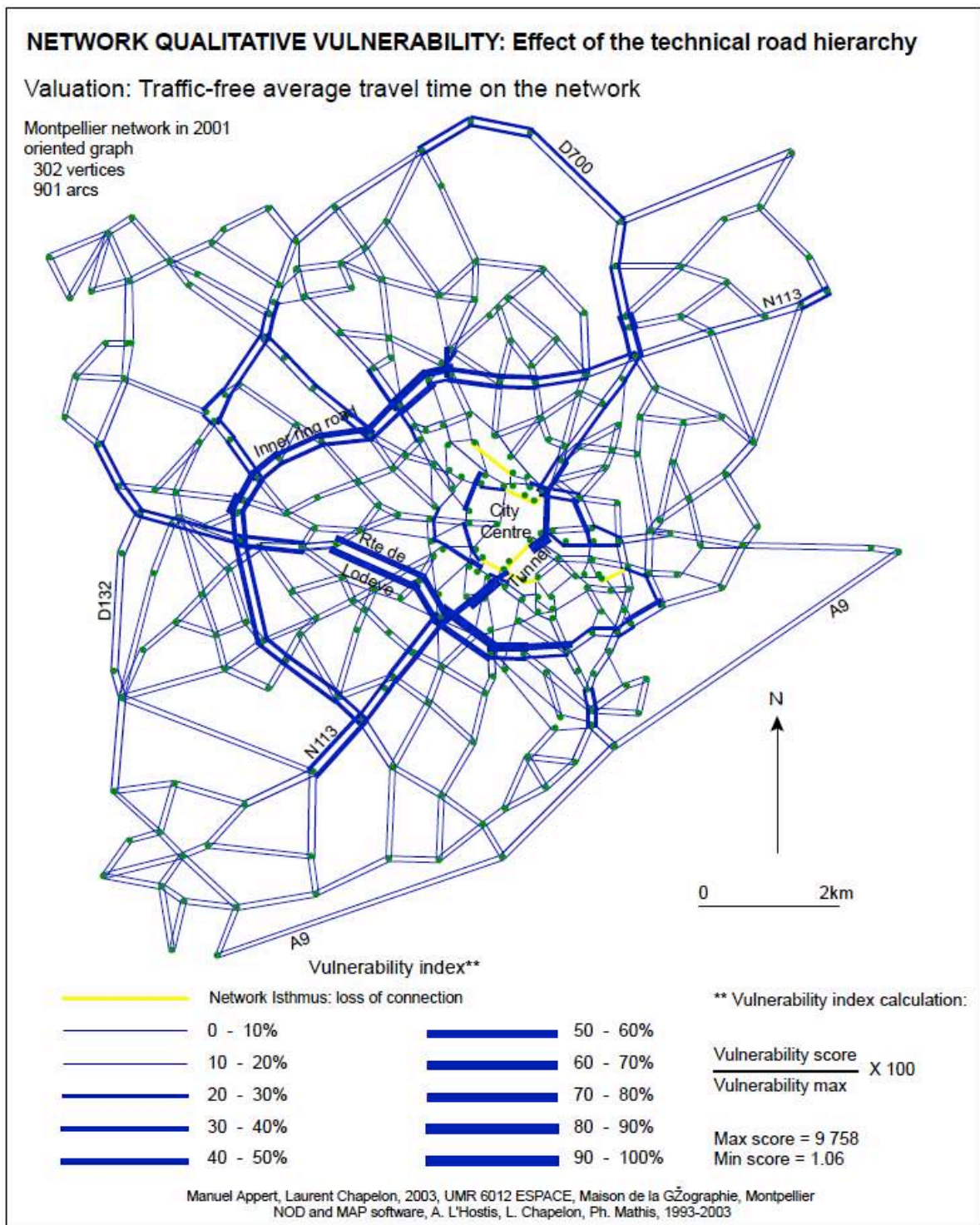
Consequently, we are able to measure the impact of the road classification (road hierarchy) on the level of vulnerability (all risks being equal).

The introduction of new roads at the top of the hierarchy has resulted in an increased concentration of vulnerability on a few links (Figure 8):

The vulnerability pattern has changed from a radial to a circum-radial structure. Ring roads are now well established (the inner ring road, the D700 and Route de Lodève, but not the A9 motorway because of its remoteness).

Vulnerability is dual. On the one hand, network is potentially exposed to severe paralysis, but on the other hand, this reflects past transport policies that sought to segregate and hierarchise traffic flow on suitable roads and prevent routes from concentrating in the centre of town.

FIGURE 8 – NETWORK QUALITATIVE VULNERABILITY



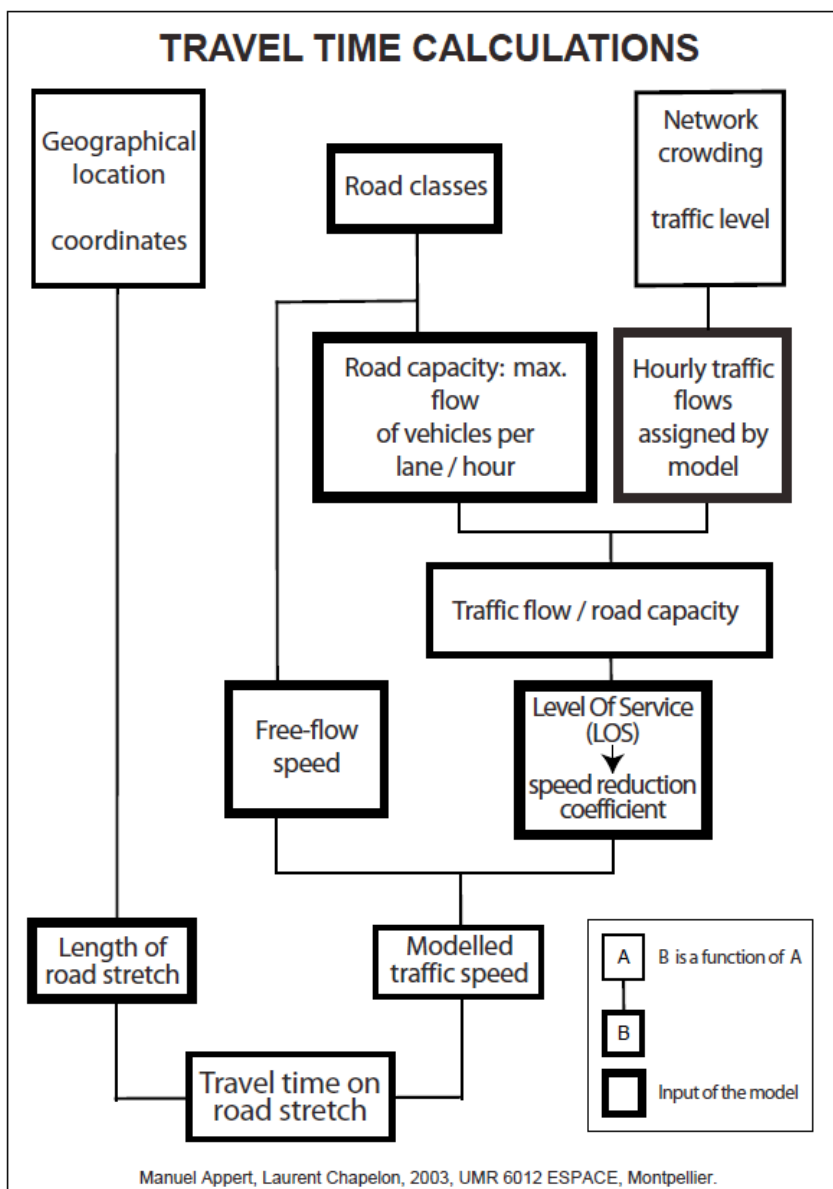
4. Network functional vulnerability

Whether relating to arc or vertex vulnerability, a given network may be predisposed to be unable to cope satisfactorily with incidents as we have seen in Section 2. These components can be analysed separately and vulnerability calculations can take only one parameter into account. In the graph valuation process, we characterise each arc with a length value, a qualitative attribute relating to the road class and its level of use or crowding. In this third case, we evaluate accessibility by adding the rush-hour speed valuation, which is the maximum attainable speed given legal limits, road characteristics and the level of crowding on the network. We thus measure the propensity of network crowding to vulnerability. We define the network's level of crowding by the following inputs:

- the number of vertices, and
- the rush-hour flow speed on links connecting pairs of vertices.

A method for integrating real-time rush-hour travel speed into accessibility calculations has been developed (Appert and Chapelon, 2002) (Figure 9).

FIGURE 9 – TRAVEL TIME CALCULATIONS



This simulation requires congestion modelling in order to obtain specific travel speeds for each link of the network for the given time period. We have chosen evening rush-hour speeds (5-6 p.m.) to model maximum crowding conditions on the network. There are several ways to model congestion, depending on whether we consider it as coming from the links or the junctions (e.g., traffic-light capacity). For this meso-scale approach, microscopic congestion modelling was inappropriate, too time-consuming and produces results that are not significantly more accurate than more traditional link modelling (HCM, Cohen). Figure 9 summarises the steps of the modelling process. For each link (arc in the graph), we have computed:

- a maximum speed (max. speed)
- a given capacity (functions of the road characteristics –capacity and max. speed)
- and the assigned hourly flows between 5 and 6 p.m. (modelled by emme/2).

For each type of road (road class), a speed-flow function applies, enabling us to calculate the effective travel speed on the links.

One might postulate that in a congestion simulation, modelled hourly traffic flow (given by emme/2 traffic model) should be reassigned for each removal or iteration. While some reroutings can occur under certain conditions, in our case, traffic blockages are of an accidental nature and therefore cannot be anticipated.

Consequently, we are able to measure the impact of the road classification (road hierarchy) on the level of vulnerability (all risks being equal) and use, in other words, how the importance of highways and new high-speed roads can influence exposure to risk.

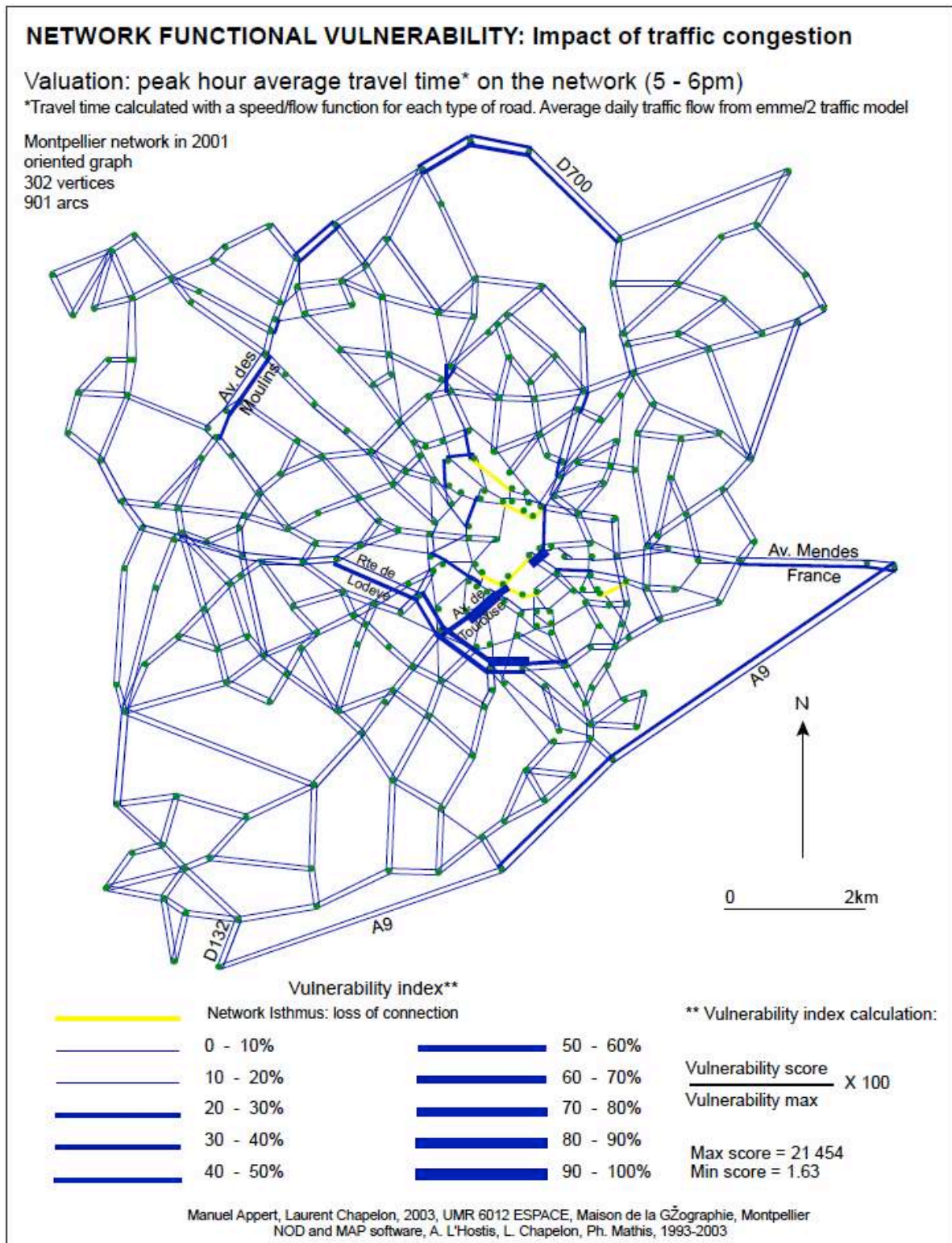
How congestion tends to destabilise the whole system by reducing concentration on the main links (Figure 10) :

Note that the maximum value is almost twice as high in absolute terms as in the previous scenario. This can be explained by greater differences in travel speeds because congestion does not affect links in the same way. As for the calculation process, the difference in relation to the reference value is greater because of degraded traffic conditions on the alternative routes.

The hierarchy appears to be undermined by congestion. Vulnerability is more widespread, main roads don't know longer seem able to cope and routes are being diverted to less suitable roads. This can result in greater "rat-running" on the secondary network, which is not suitable for today's high flows of traffic.

The A9 motorway, far from being saturated, is playing a bigger part in conducting east-west cross routes.

FIGURE 10 – NETWORK FUNCTIONAL VULNERABILITY



Conclusion

Road networks play a specific role in the urban system. As a circulatory component, they provide spatial access to every single part of the city. Road users benefit from an almost continuous service thanks to an overlapping road network. This convenient network organisation is partly responsible for increasing exposure of interconnected roads to gridlock. When the urban road network was more homogeneous and less polarised, this exposure was less acute because travel routes were more spatially diffused. However, the addition of highways at the top of the road hierarchy has resulted in increased polarisation and concentration of traffic on some links and at key junctions.

With increasing traffic flows and innovations in the road construction industry, many cities and towns have chosen to build wider, faster roads that are either radial or orbital. This kind of infrastructure now overlaps the existing hierarchy, segregating through and local traffic, and finally forming the urban trunk road network. Should an incident occur on the main carriageways, the whole system collapses, with increased rat-running in less suitable areas causing concerns about safety, pollution and the quality of life. Consequently, the entire urban road network seems vulnerable by exposing parts of the city to decreases in accessibility.

Network vulnerability is materialised on the two distinctive factors in a network, i.e., the vertices and the arcs. The degree of vulnerability also depends on three network factors: morphology, structure and performance.

We have determined that a network is vulnerable to varying degrees according to the level of hierarchisation of its links and junctions, which leads to a concentration of routes. Surprisingly, the latest road additions have tended to increase polarisation and therefore vulnerability. The pattern of vulnerability has changed as a result, with the city centre tending to be relieved, whereas the outskirts bear the brunt of exposure. At rush hour, the deterioration of travel speeds on the major links results in less route polarisation, leading to widespread vulnerability. As traffic cannot simply disappear after the occurrence of an incident, rat-running increases sharply, resulting in high volumes of traffic on unsuitable roads.

The road network vulnerability indices that we have developed can be used by planners and road agencies to evaluate exposure to risk and to address the source of this exposure, whether it comes from the network's morphology, quality or level of use. The indices also highlight the growing importance of geographical research on the risks to which cities are exposed. In our networked, just-in-time urban lives, road travel-time reliability is extremely important and the authorities must recognise the need to manage networks to reduce exposure to gridlock resulting from incidents as much as possible. These simulations can help develop better signalling systems or improve network organisation.

Acknowledgements

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