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A methodology for road traffic resilience analysis and review of related concepts

Simeon C. Calvert[a] and Maaike Snelder[a,b]

[a]Department of Transport & Planning, Delft University of Technology, Delft, Netherlands; [b]Netherlands Organisation for Applied Scientific Research (TNO), The Hague, The Netherlands

ABSTRACT
Major and minor disturbances can have a considerable impact on the performance of road networks. In this respect, resilience is considered as the ability of a road section to resist and to recover from disturbances in traffic flow. In this contribution, an indicator is presented, the Link Performance Index for Resilience (LPIR), which evaluates the resilience level of individual road sections in relation to a wider road network. The indicator can be used to detect poorly resilient road sections and to analyse which underlying road and traffic characteristics cause this non-resilience. The method adds to related concepts such as robustness and vulnerability by also considering recovery from congestion events explicitly and by focussing on everyday operational traffic situations rather than just on disasters or major events. The LPIR is demonstrated in an experimental case on a real network in which the effectiveness of the method is demonstrated.

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1. Introduction

While it is clear that major calamities and disasters can have a considerable effect on traffic and transport systems, there is awareness that more minor disturbances in traffic and transport systems can also play an important part in reducing the efficiency of such systems. A large number of effects have been proved to influence driving behaviour and with that the ability of traffic to maintain certain speeds, and also a certain serviceability, which in turn depletes traffic flow locally, but also on a network level. The effect of weather is probably one of the variables most commonly researched for its effect on road capacity and speed reduction (Calvert and Snelder 2016; Hranac et al. 2006; Snelder and Calvert 2015). Precipitation such as rain and snow, wind, temperature and mist have all been considered (Agarwal, Maze, and Souleyrette 2005; Calvert and Snelder 2016; Cools, Moons, and Wets 2010; Maze, Agarwai, and Burchett 2006). Also the influence of the local infrastructure can have an effect on traffic flow, where poor road surfaces, (incorrect) road geometry, different speed regimes, etc. can often lead to disturbances in traffic flow. Locations on a road network where interweaving traffic flows occur are well known for their pertinent ability to disrupt smooth traffic flow and often with an unknown and erratic uncertainty of their

CONTACT Simeon C. Calvert s.c.calvert@tudelft.nl

time of occurrence (Calvert and Minderhoud 2012; Sarvi 2013; Shawky and Nakamura 2007). Obviously stochastic driver behaviour, sometimes in combination with vehicle population, is often recognised for its stochastic characteristics and with that its disturbance of traffic flow (Wagner 2012; Wu 2013). However, fluctuations between drivers and within one's own driving behaviour can be instable and difficult to quantify. Furthermore the effects of driving behaviour are often combined and exacerbated together with other local disturbances. A number of other variables can also be identified.

Disturbances do not only affect local road sections, but by definition also (complete) networks. While local effects of disturbances are often considered, it is actually the network effects that are more profound and important to recognise as this is where the greatest delays occur. The two should not be considered entirely separately, as local disturbances influence network flow and network flows in turn influence local conditions. However, the causes behind network disturbances are most often found in a local disturbance. Network performance in relation to disturbances has been researched on a number of different levels. Reliability, robustness, vulnerability, accessibility and resilience are just some concepts that can be considered of a network. In the following section, we consider the differences and overlap between these concepts and give the applicable definitions. However, it is the concept of resilience with a close focus on traffic flow that is the main focus of this contribution. The focus on resilience is not commonly made in traffic flow analysis. In case of disturbances on roads, traffic flow will often be adversely affected, also leading commonly to congestion. Many measures of disturbances on the traffic consider either the probability of disturbances or the consequence of the disturbance, or both. However, in many cases small disturbances may not lead to congestion, while the balance between congestion and no congestion may be small. Furthermore, once congestion occurs, traffic flow deteriorates; the duration before traffic returns to its original level-of-service is important to be able to quantify how widespread the adverse effect of the disturbance becomes. In both cases, road sections and networks recover from disturbances and have a direct relation to the overall performance of the network. The ability to recover from a disturbance is often referred to as resilience. Resilience research is not common within the traffic flow domain, and is found more readily in other transport domains, such as supply-chain management and logical operations (Chen and Miller-Hooks 2012; Cox, Prager, and Rose 2011; Ishfaq 2012).

In this contribution, a novel resilience methodology for road traffic is presented based upon traffic homogeneity. The methodology, the Link Performance Index for Resilience (LPIR), evaluates the resilience level of individual road sections in relation to a wider road network. Road sections are considered for their ability to avoid traffic breakdown (resistance); however, if congestion occurs also their ability to recover (recovery) from a disturbance. Current literature does not readily consider traffic performance from this perspective, while resilience's resistance and recovery parts are important to evaluate the overall performance of roads. Moreover, road performance is directly related to stable traffic flow, which we explicitly consider, and is one of the main contributions of the methodology. The significance of this research is twofold: The method allows for identification of road sections which are susceptible to traffic breakdown. These locations therefore require more attention as also stochastic fluctuations can cause these locations to show weakness. Furthermore the method allows for analysis of the characteristics of network locations with volatile traffic flow. This involves characteristics of the road infrastructure, such as surface conditions or curvature, and vehicle characteristics, such as traffic composition. This can lead to a greater understanding of the variables that most affect resilience and possibly approaches that can lead to a limitation of stochasticity and improved resilience. Such an approach that considers resilience on road networks from a traffic homogeneity point of view is unique in literature.

In Section 2, the paper first takes a detailed look at performance concepts commonly used in traffic and related fields and considers their various definitions and relevance in relation to traffic resilience. The proposed LPIR methodology is described in Section 3, followed by a demonstration of the methodology in an experimental case in Section 4. The paper concludes with the overall conclusions and discussions in Section 5.

2. Performance concepts and definitions

When considering the performance of traffic flow on a road or in a network, there are a number of performance concepts that need to be considered. It is important to be clear on the precise definition of each concept, as these vary slightly between scientific domains and even within domains. There is also a certain amount of overlap that means that concepts have relevance for each other. Here we will first consider the main concepts and highlight important and recent contributions. This is followed by the considered definitions in this contribution and the relationship between the concepts. The four concepts considered here are: reliability, vulnerability, robustness and resilience.

2.1. Reliability

The *Reliability* concept is well established in traffic and network analysis on a number of levels. In general one of the most accepted definitions of reliability is given by Wakabayashi and Ilda (1992) as 'the probability that a system or a unit will perform its purpose adequately for the period of time intended under the operating conditions encountered.' From this definition it is clear that reliability is concerned with the performance of a system, in our case a road or network, while it still satisfactorily functions. It is however important to note here that the study of reliability focusses on probability of this. Berdica (2002) even goes as far as to state that 'reliability studies are generally concerned with probabilities only'. This gives a very definitive explanation of what reliability studies aims to achieve. However, it is argued that such a technical definition does not consider perception of users (Nicholson 2007; Nicholson et al. 2003). It is important to identify expectations of users as they will only evaluate a system as reliable if their expectations are met (Nicholson et al. 2003). For this it is also important to realise that both the frequency and the consequence of a disturbance are relevant in an individual's evaluation process. Jenelius, Petersen, and Mattsson (2006) make a further distinction by stating that from an individual's perspective a system can be seen as a binary decision: it is either reliable or not, while from an aggregate point of view some users will find a system reliable, while others will not. This underlines also a strong subjective aspect of reliability analysis. A wide range of reliability measures have been developed in the past decades. These differ on the one hand for their application area and in their approach to reliability analysis and often consider slightly different definitions of reliability. One may consider capacity reliability (Chen et al. 1999, 2002; Church and Scaparra 2007), connectivity or terminal reliability (Bell and Iida 1997; Chen, Bell, and

Kaparias 2007; Grubesic, Murray, and Mefford 2007; O'Kelly and Kim 2007; Wakabayashi and Ilda 1992), and travel time or cost reliability (Bell and Schmöcker 2002; Bell 1999; Carrion and Levinson 2012; Chen, Skabardonis, and Varaiya 2003; Tu et al. 2012), most of which can be applied to either individual road sections or on network level. Other classes of reliability to be identified are also behavioural reliability (Clark and Watling 2005; Lo and Tung 2003; Mirchandani and Soroush 1987; Yin and Ieda 2001) and Potential reliability (Bell 2000; Bell and Cassir 2002; Berdica 2002; Clark and Watling 2005). It is not in the scope of this paper to explain each type of reliability; however it should also be realised that each still relates to the general definition of reliability.

2.2. *Vulnerability and robustness*

Resilience is related much closer to robustness and vulnerability than to reliability. There is a sufficient similarity for it to be useful to review components of both robustness and vulnerability before looking at the relevant components for resilience. Both robustness and vulnerability will be considered together as they are near enough each other opposites and therefore will generally make use of the same components and indicators.

When discussing reliability, one is considering the proper working of a system. *Vulnerability* on the other hand considers the improper working of a system. However, it may not entirely be seen as the opposite of reliability. To expand, a well-regarded definition of vulnerability in a road transportation system is that 'vulnerability is a susceptibility to incidents that can result in considerable reductions in road network serviceability' (Berdica 2002). Husdal (2004) goes on to state that serviceability then describes the possibility to use a system during a given period. Susceptibility in this definition on the other hand indicates a probability of an occurrence. Hence that vulnerability may be considered a two-component concept in which probability and consequence are the two main attributes; probability of susceptibility, with a consequence for the serviceability. A similar view is also argued by Jenelius, Petersen, and Mattsson (2006), in which some disadvantages of this approach, as also mentioned by Sarewitz, Pielke, and Keykhah (2003), are mentioned. The main disadvantage being that estimation of probabilities of uncertain events is very difficult as some events are too rare to accurately derive from empirical data. However when considering more regular disturbances in traffic flow, this difficulty dissipates somewhat. In another definition of vulnerability by Taylor and D'Este (2003) only the consequence of an incident is considered, while the probability of a disturbance is ignored or presumed unquantifiable.

Robustness is a concept that has more recently been developed for road traffic networks. A general definition of robustness is the 'the ability of a system to resist change without adapting its initial stable configuration' (Wieland and Wallenburg 2012). For roads networks a definition of robustness is given by Snelder, Van Zuylen, and Immers (2012) as 'the extent to which, under pre-specified circumstances, a network is able to maintain the function for which it was originally designed'. Both Snelder, Van Zuylen, and Immers (2012) and Berdica (2002) state that robustness is an interchangeable opposite of vulnerability in relation to road networks. However, this is only true up to the point that vulnerability must place a greater emphasis on probability as it considers the occurrence of disturbances, while robustness considers the prevention of detrimental effects of disturbances. It is possible to only consider the effects of a disturbance, but more often than not one will also want to know its rate of recurrence. A robust network has the capability to compensate for disruptions on network links with relative ease and with only a small deterioration of performance (Sullivan et al. 2010). Therefore, a major difference compared to reliability is that robustness considers how a network can maintain its function while suffering a disturbance and therefore focusses more on the *effects* of a disturbance, while reliability is more concerned with the probability of a disturbance. Following from the definition, a robust network can allow a decline in performance as long its function is maintained, and while probability is not the main focus, the term 'extent to which' indicates a clear possibility to quantify robustness (Snelder, Van Zuylen, and Immers 2012).

Different approaches are found to classify vulnerability and robustness. On the one hand, accessibility and network efficiency are applied as main indicators in which the network geometry is seen as a more important factor (Chen and Miller-Hooks 2012; Jenelius, Petersen, and Mattsson 2006; Taylor and D'Este 2007). On the other hand, some apply an approach which considers the importance or criticality of links to be focal point (Scott et al. 2006). Jenelius, Petersen, and Mattsson (2006) makes a distinction between exposure and criticality on a network level. The exposure indicator covers the position of links and the connectivity of links on a network, while the criticality gives an indication of how important or critical a link is. Srinivasan (2002) states that there are four types of factors: *deterministic, quantitative time-varying, qualitative measures* and *random factors*. These factors describe various attributes that may be classified in four categories: *network characteristics, traffic flow, threats* and *neighbourhood attributes* (El-Rashidy and Grant-Muller 2014; Srinivasan 2002). Within these categories a similar trend is found with different descriptions; networks and infrastructure characteristics account for the supply characteristics of network links, traffic flow basically entails the demand on a network, while threats identifies weaknesses in a network and neighbourhood attributes the connectivity or accessibility of network links. Snelder, Van Zuylen, and Immers (2012) consider robustness more as an umbrella concept, which includes resilience among other parts. However, here we will refer to robustness as a single concept which overlaps, but does not enclose resilience.

2.3. Resilience

The final and main concept to be considered here for road and network performance is resilience. *Resilience* is a concept that has been recognised a number of times within the traffic domain to be of possible relevance without much research being performed (Berdica 2002; Nicholson 2007). In other transportation domains, resilience is more recognised, such as in the transport-related areas of logistics and supply-chain management (Chen and Miller-Hooks 2012; Cox, Prager, and Rose 2011; Ishfaq 2012). Chen and Miller-Hooks (2012) define a resilient network as a network that is able to recover from disruptions. This ability depends on the network structure and activities that can be undertaken to preserve or restore service in the event of a disaster or other disruption. Goldberg (1975) states that two main attributes are relevant for resilience, namely the level of disturbance and the speed at which the system can recover from the disturbance. Berdica (2002) further states that resilience could be described as the capability of reaching a new state of equilibrium, however in the case of traffic flow, a new equilibrium state may resemble or equate to the original undisturbed state. Bankes (2010) states that it is tempting to define robustness and resilience synonymously. However, he goes on to say that robustness can be generally understood as the ability to withstand or survive external shocks; to be stable in spite of uncertainty. Resiliency involves the ability of a system to recover from disturbances. Recovery implies a failure of robustness on a shorter time scale than that at which the system is judged to be resilient. This means that a system may be deemed as not being robust, while it may be considered resilient.

In this research, we therefore define resilience as 'the ability of a system to cope with disturbances and recover its original function after a loss of function'. Here the term 'to cope with' indicates that to measure resilience, does not require a state of 'functional failure' to be measured. A system that can easily cope with a disturbance may be deemed more resilient than a system that only just manages to cope, as a different more extreme disturbance may cause the latter to lose function in any case. However when a system experiences functional loss, it may still be deemed resilient, albeit to a lesser extent, if it is able to promptly recover.

While resilience is sometimes mentioned in relation to traffic flow and networks, research into descriptive methods is limited. Some authors describe resilience from an organisational and economical perspective (Bruneau et al. 2003; Nicholson 2007; Reggiani, De Graaff, and Nijkamp 2002; Rose 2009), while resilience is discussed more explicitly in other domains. Within road network research, there is also an area of research that involves resilience in case of disasters (Faturechi and Miller-Hooks 2014). In these works the focus tends to be more on decision frameworks, and therefore we will not focus on this area of research here. A few suggestions for more generic attributes in resilience are given here based on some of these other transport-related domains. These are merely meant as an indication from other disciplines, rather than an exhausted review of resilience in the whole transportation domain.

In their review of transport security, Reggiani (2013) cite four dimensions for *resilience: robustness, redundancy, resourcefulness* and *rapidity* (Bruneau et al. 2003). Robustness demonstrates the need to consider the avoidance of serviceability for a disturbance as part of resilience as a whole, where redundancy of unused capacity may be addressed. However when serviceability is affected, resourcefulness and rapidity become relevant. Resourcefulness relates to stabilising measures, either from within a system itself or externally applied (such as traffic management in traffic). Rapidity relates to the importance of a rapid return to an acceptable level-of-service. It is further stipulated that the main aspects to consider should aim to reduce *probability of failures*, the *consequences from failures* and the *time to recovery*. Minimisation of the resilience over time is also a component of this, as often found in evacuation studies (Kim, Lee, and Lee 2017).

In intermodal freight transport, Chen and Miller-Hooks (2012) present a resilience indicator. The main premise applied considers the 'the level of effort (cost, time, resources) required to return the network to normal functionality (or a fixed portion thereof)'. Here the main focus is on the recovery process and the ability to achieve a return to required level of functionality or serviceability. From this it is also clear that a complete return to the same level of serviceability is not required, but rather a predefined acceptable level of serviceability. The occurrence of (major) disturbances is considered as an unknown random effect; therefore, less attention is spent on prevention of a disturbance leading to a loss in serviceability. Some variables applied are:

- Recovery activities.
- Change in capacity after implementation of recovery activities.

- Travel time (incl. Maximum travel time).
- Time to implement recovery activities (incl. Maximum implementation time).
- Cost of recovery (incl. Maximum allowable cost).
- Network connectivity.

In other research on transportation network, Murray-Tuite (2006) describes a simulation approach for resilience in which a system optimum approach is compared to a user equilibrium approach. In her research she identifies 10 main dimensions to be considered for resilience:

- Redundancy.
- Diversity.
- Efficiency.
- Autonomous components.
- Strength.
- Collaboration.
- Adaptability.
- Mobility.
- Safety.
- Ability to recover quickly.

Some of these attributes are more relevant for transportation networks rather than traffic networks, such as collaboration or autonomous components. However, other attributes and the general premise give a good insight into the type of attributes that should be considered.

2.4. Overview

Form the various descriptions it should be apparent that although there are varying definitions for the described concepts, there is a general level of consensus on their meaning. The main definitions of the various concepts are summarised as:

Reliability

- The probability that a system or a unit will perform its purpose adequately for the period of time intended under the operating conditions encountered.

Vulnerability

- A susceptibility to incidents that can result in considerable reductions in road network serviceability.

Robustness

- The ability of a system to resist change without adapting its initial stable configuration.

Resilience

- The ability of a system to cope with disturbances and recover its original function after a loss of function.

Table 1. Overview of performance concepts and their relevance.

	Reliability	Vulnerability	Robustness	Resilience
Description	Probability of serviceability	Susceptibility of serviceability loss	Ability to maintain serviceability	Ability to maintain and recover serviceability
Disturbance relevance	Probability of occurrence of ...	Not withstand the effects of ...	Withstand the effects of ...	Withstand and if necessary recover from ...
Probability relevance	Main focus – indicates proximity to perfect performance	Facilitating – indicate chance of function loss	Facilitating – indicate chance of function loss	Facilitating – indicate recovery ability
General application	Both locally and on network	Mainly on network level, but also locally applicable	Mainly on network level, but also locally applicable	Mainly local, but also applicable on network level

All these concepts are connected by their description of the performance of a system. Each concept highlights a different part of the performance. Reliability focusses very much on the probability of the system performing, while vulnerability on the other hand considers the probability of improper working of a system. However it may not entirely be seen as the opposite of reliability, as described in Section 2.2. Robustness on the other hand focuses on a system's ability to maintain its purpose and to withstand or survive external shocks; to be stable in spite of uncertainty. Resilience involves both resistance to disturbances as well as the ability of a system to recover from disturbances. Recovery implies a failure of robustness on a shorter time scale than that at which the system is judged to be resilient. This means that a system may be deemed as not being robust, while it may be considered resilient.

It is clear that *probability* on the one hand and *disturbances* on the other hand are important aspects that define the definition of the concepts. Furthermore, the concepts will be applied in different ways due to these differences. To highlight the relevance of probability, disturbances and general application, these aspects are given per concept in Table 1 to more easily distinguish between the concepts. The various concepts are connected as previously described in this section. A good overview of the interdependent relations between the aforementioned concepts is given in Figure 1, adapted from Wang et al. (2014).

3. Methodology

Many of the previously described measures and components are keyed very much towards network performance even if many calculate local road section performance to obtain a network score. As defined in a previous section, a main application area here for resilience is very much on the performance of local road sections. In this research there is a greater emphasis on the determinants of certain attributes, rather than only on the resulting effects. A previous example of a poor road surface is an example of such a determinant, while a lower speed for that road section is the resulting effect. As we define resilience as 'the ability of a system to cope with disturbances and recover its original function after a loss of function', it may be seen as an extension of robustness/vulnerability as it considers the ability of a system to cope with disturbances. Though it differs in the sense that it also considers the recovery process explicitly and as an important part of the concept. Moreover, the focus in this contribution is more on traffic flow rather than network infrastructure.

We start by stating therefore that resilience exists out of two main parts: *resistance* and *recovery*, as is found in the majority of the cited literature. The *resistance* part incorporates the extent to which a road section or network is robust and can resist functional loss under

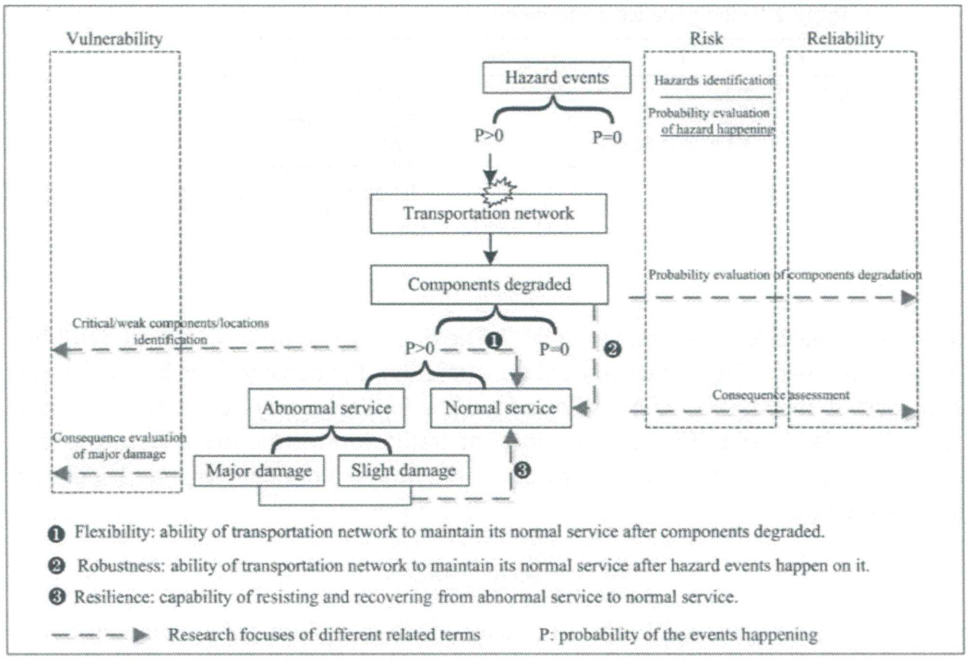

Figure 1. Relationships between main concepts (taken from Wang et al. 2014).

stress and is comparable to robustness. The *recovery* part of resilience is what sets the concept apart from robustness/vulnerability and describes the ability of a road section to return to an acceptable level-of-service.

3.1. Resistance

We define the ability of the traffic system to resist a disturbance (resistance) as 'the ability to avoid going into a state of congestion'. To this extent we quantify this as the ability of a road section to maintain a density lower than the critical density: $k < k_{\text{crit}}$. Writing this as an index which represents stability below a value of 1, gives:

$$\text{Index} = \frac{k}{k_{\text{crit}}}. \tag{1}$$

The density and the critical density can be derived from a number of other components. In traffic flow, in relation to the influence of disturbances, we have identified the following components for the density and the critical density in an uncongested flow (Table 2).

Substitution of the components into Equation (1) gives the derived resistance equation:

$$\text{Resistance} = \frac{\left[\frac{q+\psi^{q}}{v}\right]}{\left[\frac{q_{\text{cap}}(g,h)\cdot f+\psi^{\text{cap}}}{v_{\text{crit}}}\right]}. \tag{2}$$

Table 2. LPIR resistance components.

Density	k	Critical density	k_{crit}
Q	Flow	q_{cap}	Road capacity
V	Speed	g	Road characteristics
ψ^q	Volatility of flow	h	Traffic characteristics
		ψ^{cap}	Volatility of capacity
		f	Temporal capacity reductions (i.e. incidents)

The equation is valid for a set time interval, T. The dependence on time is excluded from the equation for readability. Here we see in the numerator the density given by the 'volatile flow' divided by the speeds, which follows from the fundamental relation of traffic flow: $k = q/v$. The volatility of traffic flow describes the traffic flow increased with a measure of volatility, describing the stochastic behaviour of the flow in a predefined period, identical to the time interval, T:

$$\psi^q = \frac{1}{2}(q_{max} - q_{min}). \tag{3}$$

Note that $(q + \psi)$ does not need to correspond with a maximum value of q in the considered time period, as the gravity of the values may be skewed higher or lower. Fluctuations in the speed can also be included in this volatility factor; however are expected to follow the fluctuations in the flow and are therefore not required. In the denominator, the critical density is given, which also incorporates the fundamental relation. The speed is the critical speed by definition, and is dependent on the road and traffic characteristics. The critical flow is described as the capacity reduced by a temporal capacity reduction factor and also includes a volatility component. It is given as a function of the road and traffic characteristics. The volatility of the capacity is given here as

$$\psi^q = \frac{1}{2}(q_{cap}.\text{max} - q_{cap}.\text{min}). \tag{4}$$

The road characteristics component g represents the influence of the infrastructure and depends on variables, such as the maximum speed limit, number of lanes, lane width, gradient, curvature, road surface and so on. The traffic characteristics component h represents variables such as vehicle types and characteristics, vehicle dimensions, driver types and so on. A further quantification of these components is not given in this contribution, but is rather recommended for later research. However, some thoughts are given on how these terms may be interpreted and calculated. Both components influence the road capacity q_{cap}, which makes a lot of sense, since capacity of a road is a direct consequence of driver behaviour. Depending on the time of day, the driver population may vary, for example, during peak periods it may be expected that more experienced drivers are on the road that have a greater time-constraint compared to non-peak traffic, therefore leading to a higher capacity. Also, the composition of traffic is highly relevant. The percentage of trucks, for example, will affect capacity due to their slower speeds, and different ability to accelerate and decelerate compared to cars. Traffic is also influenced by infrastructure. A higher speed limit may lead to a greater distribution of speeds, which in turn is expected to a have a negative effect on capacity. It is well known that an increase in the number of lanes is not linearly

Table 3. LPIR recovery components.

Recovery components			
Δq	flow volatility, $q_{in} - q_{out}$	q_{in}	inflow
q_{cd}	capacity drop (absolute)	q_{out}	outflow
$v_{eq}(q)$	speed, derived from fundamental diagram		

related to an increase in capacity, mainly due to more lane-changes. Other aspects of infrastructure, such as a gradient will result in lower capacities, especially where there are more trucks present on a road.

There are two obvious ways to calculate the effects of these infrastructure and traffic components: directly from data for a specific location, or through a generic derivation of relationships between the various aspects, of which some have already been mentioned. The first approach would involve performing empirical analysis on the desired location using a general capacity estimation method, such as the Product Limit Method (Brilon, Geistefeldt, and Regler 2005). This would produce an indirect calculation of the effects of infrastructure and traffic, as the capacity would be the resulting indicator, rather than the individual aspects for g and h. The second approach involves performing data analysis to estimate the individual effects of each aspect, such as multivariate analysis in relation to the capacity. By deriving the individual influence of each aspect and component, an estimate can be made for any other road section and under specific traffic conditions.

3.2. Recovery

Corresponding to the definition given of the resistance part, the recovery part is defined as 'the ability come out of a state of congestion'. This is quantified as the ability of a road section to regain a density lower than the critical density from its current state: $k > k_{crit}$. This index allows use of the same Equation (1). The main additional components identified as relevant for determination of the recovery are given as Table 3.

The recovery equation is derived in a similar fashion to the resistance equations, making use of the fundamental relation and a further expansion of the underlying variables, but in this case for a congested traffic state. The two main traffic variables that influence the recovery of a road section are found to be the resulting *capacity drop* in a section and the difference between the in- and outflow of traffic into a road section. From Equation (5) it is clear that a higher capacity drop will reduce the speed at which recovery can happen, as well as a higher inflow compared to the outflow.

The recovery equation is then given by

$$\text{Recovery} = \frac{\left[\frac{q+\Delta q}{v_{eq}(q)}\right]}{\left[\frac{q_{cap}(g,h)\cdot f - q_{cd}}{v_{crit}}\right]}. \tag{5}$$

Again, the equation is valid for a set time interval for which the dependence on time is excluded from the equation for readability. Here, $v_{eq}(q)$, further represents the speed derived from the fundamental diagram with input: q. Written in full, this corresponds to

$$v_{\mathrm{eq}}(q), = \frac{q}{\left[k_{\mathrm{crit}} + \left(1 - \frac{q}{q_{\mathrm{cap}} - q_{\mathrm{cd}}}\right) \cdot (k_{\mathrm{jam}} - k_{\mathrm{crit}})\right]}, \tag{6}$$

where k_{jam} is the jam density and k_{crit} is the critical density.

3.3. General link performance indicator for resilience

As we define resilience in traffic flow as the combination of both resistance and recovery, the combination of the previously described equations results in the LPIR and is given by:

$$\mathrm{LPIR} = \sum_{t=0}^{T} \left\{ \begin{array}{ll} \dfrac{\left[\dfrac{q + \psi^{q}}{v}\right]}{\left[\dfrac{q_{\mathrm{cap}}(g,h) \cdot f + \psi^{\mathrm{cap}}}{v_{\mathrm{crit}}}\right]} & \text{for } k \leq k_{\mathrm{crit}} \\ \dfrac{\left[\dfrac{q + \Delta q}{v_{\mathrm{eq}}(q)}\right]}{\left[\frac{q_{\mathrm{cap}}(g,h) \cdot f - q_{\mathrm{cd}}}{v_{\mathrm{crit}}}\right]} & \text{for } k > k_{\mathrm{crit}} \end{array} \right\} \Big/ T. \tag{7}$$

Note that each variable is valid for a set time interval. For readability, the notation of the dependence on t has been omitted from the equation. The total LPIR score per road section is the average over all time intervals for the considered period and therefore the LPIR is a non-time dependant and static.

The LPIR can be applied to any road section to give an indication of the relative resilience of that road section compared to other road sections. A value of LPIR ≤ 1 indicates that a road section is able to resist a significant drop in level-of-service and therefore remain uncongested and by definition must be considered resilient as well as robust. However a road section that does suffer a drop in level-of-service, but can recover promptly should also be considered resilient as resilience considers the ability to recover from a disturbance or loss of service. However in the latter case, the road section may not be considered robust, as a failure event occurred. One cannot state that a value above LPIR > 1 is always non-resilient. Normalisation of the LPIR may be applied, as this may make comparison between values from different road sections easier. However this has the drawback that the quantitative interpretation of the index is lost and is not performed in the experimental case later in the paper.

3.4. Stochastic link performance indicator for resilience

The presented description of the LPIR given in Equation (7) is a deterministic score for resilience. However increasingly the importance of explicitly considering stochastic fluctuations in traffic is being seen as relevant and often necessary. Therefore, a stochastic representation of the LPIR is also relevant. Incidentally it is not that difficult to transform LPIR for a stochastic representation. The variables representing the flow from the original LPIR should be described as random variables rather than deterministic and must be further condensed, resulting in:

$$\boldsymbol{LPIR} = \sum_{t=0}^{T} \left\{ \begin{array}{ll} \dfrac{\left[\dfrac{\boldsymbol{q}}{v}\right]}{\left[\dfrac{\boldsymbol{q}_{\text{cap}}(g,h) \cdot f}{v_{\text{crit}}}\right]} & \text{for } k \leq k_{\text{crit}} \\ \dfrac{\left[\dfrac{\boldsymbol{q} + \Delta q}{v_{\text{eq}}(q)}\right]}{\left[\dfrac{\boldsymbol{q}_{\text{cap}}(g,h) \cdot f - \boldsymbol{q}_{\text{cd}}}{v_{\text{crit}}}\right]} & \text{for } k > k_{\text{crit}} \end{array} \right\} \Bigg/ T. \tag{8}$$

Note that the main changes relate to the representation of q, which is now the random variable $\boldsymbol{q}$. Furthermore the volatility variables become obsolete in a stochastic version, as they were used as a measure of variability, which is now incorporated in the random variables of the flows and capacities. It is also possible to represent the incident reduction factor as a random variable, as well as the speed and critical speed. However it is chosen not to do that here and consider stochasticity only from the flow and capacity variables.

3.5. Considerations and component sensitivity

The presented methodology differs in its approach to many other methods that have previously been presented for similar measures, mainly in the area of robustness. The first main difference is the focus on specific road sections, rather than on a network performance. The second one is the explicit consideration of traffic flow dynamics, where many other methods consider more static descriptive variables. In relation to consideration of local road sections, an implicit consideration of the influence of other bottlenecks and connectivity to the rest of the network is present. Downstream congestion that reaches an arbitrary road section will affect the LPIR score of that section in conjunction with the severity of the congestion. However the opposite does not apply. That is the network effect of congestion caused by a considered road section on the rest of the network. This is a drawback when one wishes to expand the method to be used to calculate a network index. In relation to consideration of traffic flow dynamics, this method aims to seek out the core reasons behind resilience or the lack of, and offers the possibility to connect the resilience score to the causes. At the highest level, this is only calculated from traffic data, while further adding detail to the g and h terms, denoting road and traffic characteristics, allows explicit causality to be derived. This is not performed in this paper though.

The variables applied in the method have been tested for their sensitivity, while a few other variables that were considered have been shown not to be of great relevance. The choice of the time interval, T, has been analysed for its effect on the results. The time interval is mainly relevant for the volatility variables (ψ), including the delta flow variable (Δq). The outcome of the analysis shows that the absolute value of LPIR does shift slightly, but in relative terms there is a limited effect. Therefore, some numerical fluctuations are possible, but limited. In any case not sufficiently large enough to influence the analysis of the road sections. When delta flow is not included, the LPIR shows a higher sensitivity for higher T values ($T = 15$), while for lower T values (i.e. $T = 2$), the exclusion of delta flow does not influence the LPIR score. As the influence of delta flow requires a higher T value and the relative difference is not large between T values, a value of 15 min is viewed as a suitable value, as this allows variation in flows to be considered in LPIR. The analysis of this variable is shown in Appendix. Besides the Δq and T variables, a further volatility term for congested traffic was considered as well as a volatility value for the speed and critical speed. We found that congested traffic was more stable than uncongested traffic and that the Δq term already included the relevant variations in recovery, such that the inclusion of a volatility term for the recovery did not have a large effect. Including a volatility terms for the speed and critical speeds in the resistance equation also did not possibly influence the scores. The traffic speeds were found to include too much noise to be included as they made the results messy, while the flow volatility already captured many of the fluctuations, but in a more stable manner. The critical speed was found to be rather stable for most locations and between different breakdown events (consistently between 70 and 75 km/h) and therefore added little to the overall method. Therefore these additional volatility variables were not applied.

A further consideration may be the application of the LPIR, or a derivative thereof, for non-recurrent traffic breakdowns, such as traffic incidents. The methodology was originally designed to capture regular patterns from a wider data set over many days instead of focussing on single breakdowns. However, the method could be adjusted to focus on the effects of incidents and make predictions in a similar fashion to the LPIR by considering the parameters of an incident, such as the reduction in capacity, the change in traffic speed, driver behaviour and of course the recovery time to return to full capacity. If previous incidents were to be analysed for these variables, and additional probabilities of an incident occurring on a road section were to be calculated from historical data, a score per road section may be able to be given. Changes would need to be made to the approach, however may be possible and is recommended for later research.

4. Experimental study results

4.1. Setup and network

A demonstration of the LPIR is given making use of a real network. The purpose of the demonstration is to show the applicability of the method using existing and accessible traffic data. The demonstration also acts as an indicative validation of the methodology.

This is achieved by comparison with two simple measures for both robustness and resilience, namely the *time to recovery* and the *total delay time*. The time to recovery, *TR*, per road section is defined as:

$$\mathrm{TR} = \frac{\sum_n T_n^{\mathrm{recover}}}{N} \quad \text{for } N \geq 10. \tag{9}$$

Here T_n^{recover} is the recovery time of a single congestion event, n. N is the number of congestion events per road section, while a minimum number of 10 congestion events for a single road section is required to give an estimate.

The total delay time, TD, per road section, is defined as:

$$\mathrm{TD} = \sum_{t=0}^{t=e} \frac{\mathrm{veh}(t)}{v_{\mathrm{free}} - v_{\mathrm{obs}}(t)}. \tag{10}$$

Figure 2. Considered network of the A13 and A20 motorways.

Here veh(t) is the number of vehicles on a road section in a time interval, v_{free} is the free-flow speed, which corresponds to the maximum speed limit, and v_{obs} is the observed average speed of all vehicles during the time period. In total, there are e number of time periods.

The considered network exists of two interconnecting motorway stretches to the north of the city of Rotterdam in the Netherlands (see Figure 2). The motorways are the A13 and A20 motorways and vary in width between two up to four lanes, with the majority of the road having three lanes, and include several junctions and interchanges. The network is regularly congested in the peak periods with known bottlenecks at multiple locations. The total distance of the roads is approximately 55 km long.

The data used in the case for the considered network is data taken from an extensive collection of induction loops at a distance of approximately 300–500 m. The induction loops relay 1 min aggregated data on the traffic flow and the speed of traffic. The data are from the entire year of 2009, in which incorrect working detector loops have been removed. Missing data were also filtered out of the analysis, which was often the case during night periods with sparse traffic. The occurrence of (major) incidents in the data was removed as 'outliers'. Minor incidents were harder to remove and may still be present in the data, however their influence is presumed to be very small in among the complete data for a complete year when focussing on a particular road section. Further assumptions for the analysis involve an aggregation of traffic data for capacity estimation to a minute by minute moving average aggregation level of 15 min. The specific values for the critical speed, critical density and other traffic variables are derived as specified in the methodology section per road section.

For the *time to recovery* it is assumed that traffic is in congestion when the traffic speed drops below 60 km/h for at least one time period of 15 min and traffic flow is at least 900 veh/h. This second condition eliminates the cases in which (major) incidents occur and the road is (partially) blocked and also eliminates false positives in sparse traffic. Traffic is presumed to have recovered when the traffic speed rises above 60 km/h for the 15 min aggregation.

The *total delay time* considers the difference between the free-flow speed and the observed speed. The free-flow speed here is may also be constrained, but also non-congested traffic flow. The total delay time makes use of 1-min aggregated traffic flow, which is a common approach. As the speed limits on the network are 80 and 100 km/h in parts, a reference speed of 80 km/h is selected for comparison. All 1-min aggregated traffic flow below 80 km/h leads to a delay, while traffic speeds above 80 km/h do not.

4.2. LPIR calculation

The LPIR is calculated for the network shown in Figure 2. This is performed using an aggregation time interval of 15 min, as argued in Section 4.5. Data for the entire year of 2009 are used in the experiment. Road sections are defined as the section of road between two correct working loop detectors. In this test case, the jam density of traffic is assumed as 130 veh/km per lane. Incidents are not explicitly considered, meaning that the incident reduction term is unused and has a value of 1. Capacity values are pragmatically estimated from data by taking the 99.9th percentile value for each road section. At bottleneck locations this will resemble the real capacity, while at non-bottleneck locations the value will be less important as traffic flow will either remain uncongested (captured by the traffic speed) or will be influenced by an external bottleneck with a lower capacity value.

The primary LPIR results of the experiment are shown in Figure 3 on the considered network. Values are shown to generally vary between 0 and 1.4, with one section in particular reaching a LPIR value of 2.0. Road sections with higher values are sections that should be viewed in more detail and are the sections that should be most readily considered for improvement to improve the traffic throughout and in turn the network performance, even if the network performance is not directly calculated. In Figure 3 road sections that appear with darker are the least resilient. These are road sections that have a LPIR score equal to or above 1.2, lighter indicating values around 1.0, and values below 1.0, are deemed to be road sections that have a lesser priority in comparison to the higher scoring road sections.

Using the results from the LPIR analysis, a priority list can be constructed, which indicates which road sections should be addressed with which urgency by road authorities. This list is given in Table 4, with the numbered sections shown in Figure 3. A manual check based on expert judgement is performed to give an indication of the possible reasons of each section belonging to the list and the causality of the low resilience score. Causality can be added to the analysis by making use of the traffic characteristics and road characteristics terms from Equation (7). This would exist of adding data from further relevant variables, such as data on the road surface, infrastructure geometry, traffic composition and many more. This more detailed analysis is not performed in this contribution; therefore, causality is left to expert judgement.

A deeper analysis of the results is shown in Figure 4 for the A20 motorway in the westbound direction. The figure shows the traffic speeds during an arbitrary work week along with the LPIR scores.

From Figure 4 it quickly becomes apparent that the LPIR score does not simply replicate traffic speeds, but rather focusses on the main areas in which congestion occurs. Moreover,

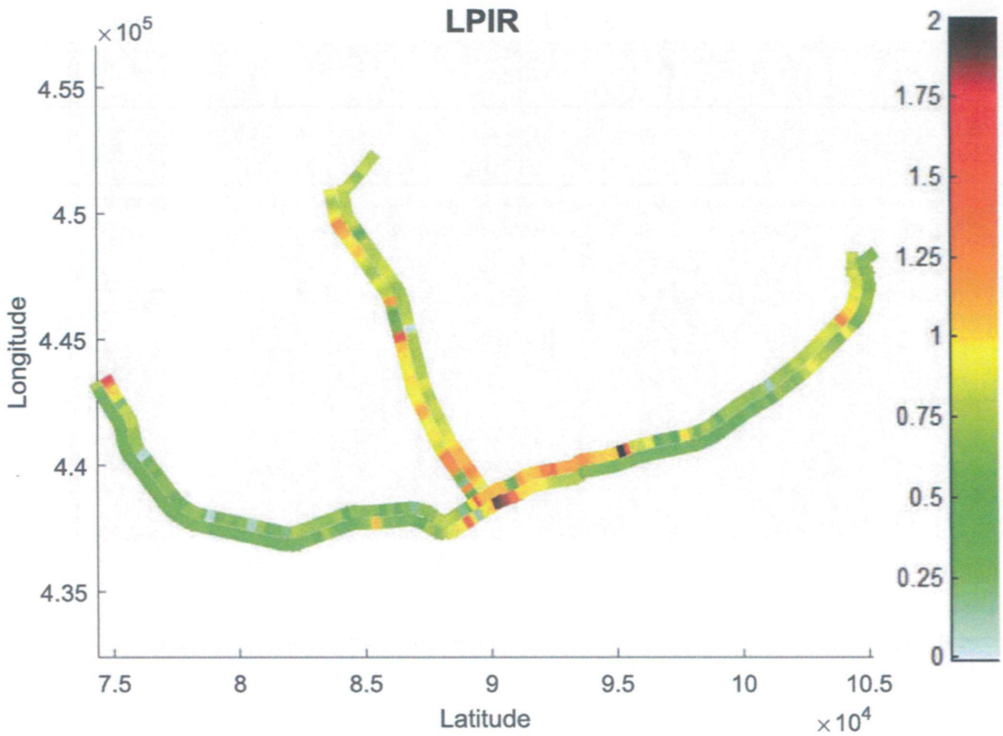

Figure 3. LPIR score per road section.

Table 4. Least resilient road sections from the A13–A20 analysis.

Section nr (see Figure 3)	LPIR value	Location description	Section type	Estimation of problem (expert judgement)
1	2.0	A20L Terbregseplein		Joining flows after interchange
2	1.9	A20R Centrum	Section with onramp	Narrow lanes, gradient and inflowing traffic on short onramp
3	1.7	A20L Kleinpolderpolein	Weaving section	Weaving section
4	1.6	A13R Delft-Zuid	Onramp	Joining flow with a bend in the road
5	1.4	A20R Kleinpolderplein	Weaving section	Weaving traffic at interchange split
6	1.4	A20L Centrum	Off-ramp	Short uphill off-ramp

the method also aims to give an indication of the ability of a road section to recover from disturbances. Road sections which suffer congestion, and are especially the cause of congestion, and cannot readily recover receive higher index scores, representing this. This can be derived at a number of places from Figure 4. The congestion in the middle of the road (around section nr 60) is more severe and lasts longer and even leads to secondary congestion upstream. In comparison, the congestion observed at the bottom of the figure (near section 100) occurs regularly during a week, but is less severe and has a tendency in a number of cases to lead to limited spillback and to dissolve faster. This is represented in the LPIR score, which is close to 1.0, therefore indicating a road section that may need attention, but has a limited negative effect.

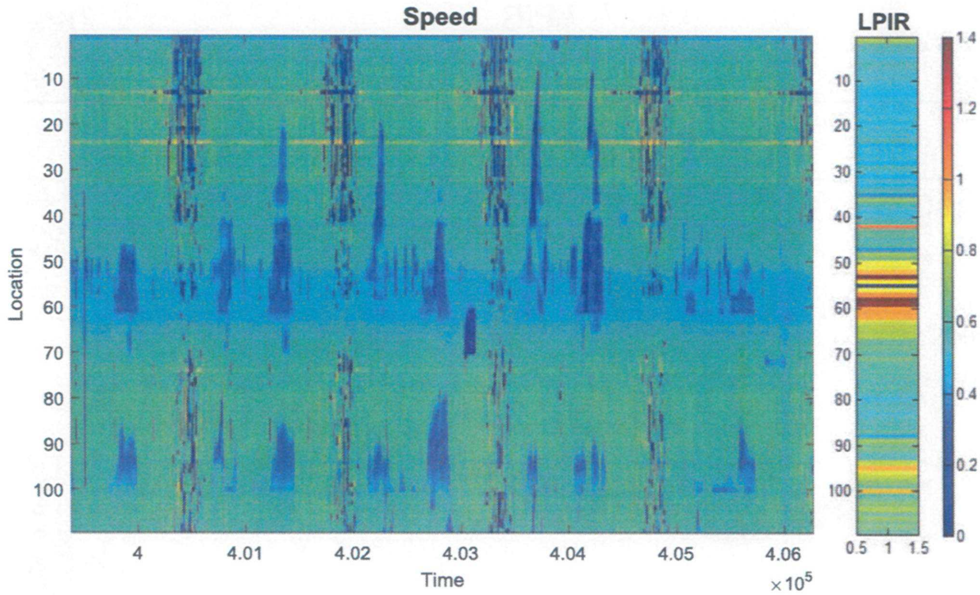

Figure 4. Comparison between speeds (left) and LPIR values (right) on the A20R (westbound).

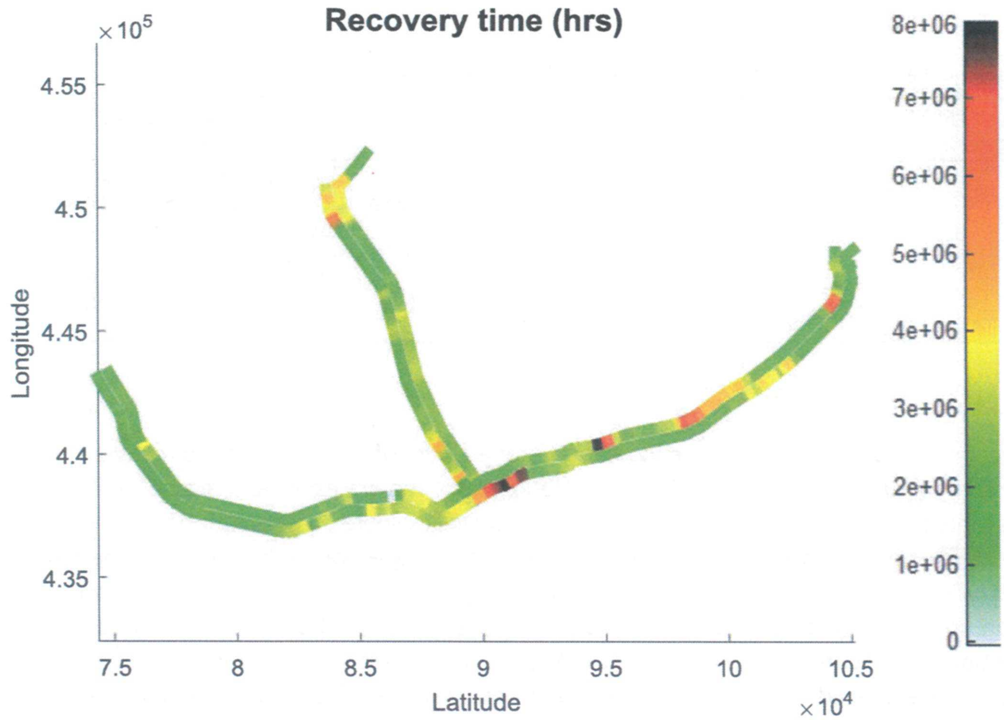

Figure 5. Average yearly recovery times per road section (h).

4.3. Comparison with other measures

In many disciplines the resilience of a system is measured by the required recovery time. The recovery time is then a measure for the recovery. Although recovery is only seen as part of the resilience definition here, a comparison with the LPIR score can be insightful. In Figure 5, the average recovery times are shown for a road section to exit congestion. It is expected that a number of locations that have a long recovery time are part of the higher LPIR locations. However, there are also a few that do not score high on the LPIR. One such example is that at the coordinates [9.8; 4.42]. Alternatively some locations with relatively low recovery times are shown to have relatively high LPIR scores, even if they are not among the highest LPIR scores. These effects are down to the combined effect of both recovery and resistance in the LPIR. If one of these aspects is low, then the overall LPIR will also be relatively low. This shows that the LPIR is a typical impact index. Despite some difference, most of the least resilient road sections are also among the road sections with the highest recovery times.

Another measure used to compare the LPIR results is the network delay, for which the results are shown in Figure 6 per kilometre distance. The total network delay is a measure that can be used to indicate robustness and therefore mainly reflects the resistance part of traffic flow. The total network delay includes a further element compared to the LPIR and the recovery time, which is the total flow. This acts as a sort of weight for negative effects of congestion and indicates also a combined effect of the number of vehicles affected and

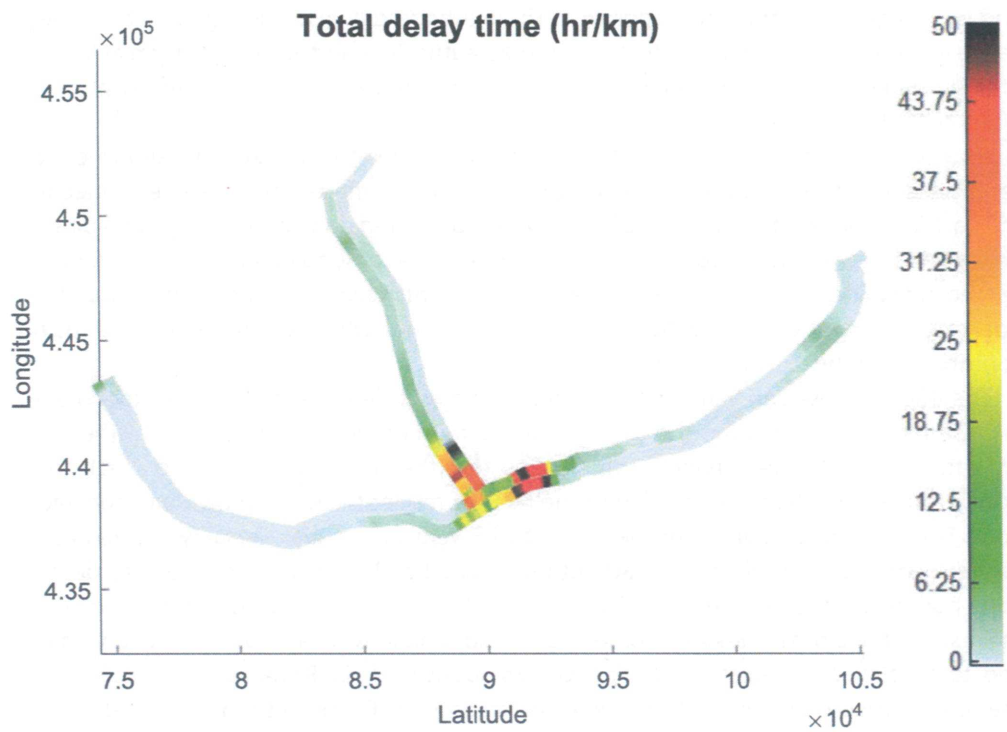

Figure 6. Total network delay in 2009 per road section (h/km).

the length of a delay. However the indicator focusses on the effect of traffic breakdown and not on the causality, which is a more important part of the LPIR. To that extent the locations shown are slightly different to the LPIR. The presence of congestion in the LPIR does not necessarily lead to the highest LPIR score. And although the network delay does indicate where most delays are recorded, it fails to pinpoint the main weaknesses in the network.

5. Conclusions and discussion

In this contribution the LPIR is presented as a new methodology to evaluate the resilience level of road sections in relation to the surrounding network making use of traffic homogeneity. The methodology considers resilience based in part on inherent fluctuations, or rather volatility, in traffic flow, which is highly relevant and has not previously been performed in such a way. The focus of the methodology is on resilience and is therefore wider than robustness, as it also considers the ability of road sections to recover from disturbances as well as the classical robustness itself. To this extent a distinction is made between a resistance part and a recovery part as part of the entire methodology. Contrary to many other works, the basis for the methodology does not focus on the network as a whole or as a generic description of the network and its parts against a certain measure. Rather the resilience is calculated in relation to the traffic flow characteristics at a flow level and the ability of road sections to maintain their predefined purpose to serve vehicles without overly experiencing congestion. The focus on homogenous and volatile traffic flows also leads many of the considered components to relate closely to traffic flow characteristics and is a unique and innovative approach. The methodology also has high practical relevance and offers a powerful tool that allows road authorities and alike to perform analyses of their road network and identify the weak links, which may demand the higher priority when considering investment.

Prior to the explanation of the method, an extensive literature review was performed to set the scene for the LPIR, but also to indicate where most efforts have been performed in the past. This showed that much has been done and is being done in reliability and vulnerability and increasingly in robustness analysis. Resilience is found in many transportation-related disciplines, such as transport networks, freight movements and logistics, but it not explicitly commonplace in traffic flow analysis. This is where the niche and the main contribution of the LPIR method lie.

The effectiveness and validity of the methodology is demonstrated in an experimental case for a small network of two interconnecting motorways to the north of the city of Rotterdam in the Netherlands. This showed that the LPIR is able to detect weak and poorly resilient locations by calculating the relative resilient value of individual road sections. For the road sections with the highest LPIR value, a manual causality is given as a further demonstration of how a road authority may be able to use the results to determine poorly resilient road sections. The calculated LPIR values are further compared with the results of two other measures for resilience and robustness, namely the 'recovery time' and 'total delay'. Many locations that performed poorly in the LPIR were also highlighted in the other measures; however, there were also important differences that further showed the strength of focussing on resilience. The recovery time merely shows locations that can quickly recover from a congestion event after a disturbance, while the occurrence rate is not considered and therefore says little about the overall impact during a longer period. On the other hand, the total delay experienced on a road section does give an overall indication of the negative effect of congestion on a road section. In comparison to the LPIR, this lacks as it does not sufficiently take into consideration where bottlenecks are present and therefore the road sections which are the cause of congestion. Congestion on a road section for a bottleneck further downstream is unfairly penalised due to the weakness of another road section. Although one may argue that this is also a part of resilience, it does not accurately contribute to the purpose of identification of the main problem areas for disturbed traffic flow and recovery from congestion and therefore a lack of resilience. We therefore argue that the analysis of the resilience offers a deeper insight into the way road sections are judged for weakness and that resilience analysis offers a complementary tool to robustness. This is especially the case when the analysis concentrates on the influence of disturbances on traffic flow at the level of traffic rather than at a higher abstraction level.

The LPIR methodology also allows for a deeper analysis of the casualty of a poorly resilient road section. This is performed through additional data analysis. This part of the LPIR was not further elaborated on in this contribution and was also not part of the experimental case. The consideration of incidents was also not part of the considered case. Both of these elements are given as recommendations for further research. Especially the analysis of resilience causality is an interesting area that can be a strong addition to the presented method, as it does not only return road sections that require attention, but also gives a strong indication of the reasons behind the lack of resilience allowing a road authority to act more precisely.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix. Sensitivity of the time interval parameter *T*

The parameter for the time interval, *T*, is relevant for the considered period in which the volatility and extreme values of the flow are measured. There is however no required value; therefore an analysis of appropriate values is carried out to test the influence of different values. This is also combined with a test of the necessity of the delta flow variable, which indicates the difference between the incoming and outgoing flows on a congested road section.

An upper bound is set of 15 min for *T*, as a higher value would lead to a less representative observation of the traffic states. It might even be suggested that 15 min is already too high; however, such a value is not an uncommon aggregation level in traffic flow theory and modelling. Figure A1 (left) shows LPIR values for the A20R (westbound) for three *T* values: 2, 5 and 15 min. From the figure, each result shows that the locations of higher values correspond between *T* values, which is not surprising. Higher *T* values show a higher LPIR score. This is also not surprising as longer time intervals allow a larger range of flows to observed, which in turn will lead to a higher LPIR. Further analysis shows that the scores between the three tested values are relatively similar. Therefore for relative comparison there is little difference. As the LPIR is applied as a relative index between road sections, we conclude that there is not a strong preference for the choice of *T* value based on its own sensitivity alone.

In Figure A1 (right) the effect of the *delta flow* variable is considered together with different *T* values: 2 and 15 min. This comparison shows that the value of *T* does matter for the results of LPIR when delta flow is included. This can be seen in the difference between the first and second result, with or without the use of the delta flow term. However when $T = 2$, there is no difference between the LPIR scores with or without delta flow, which can be seen from the third and fourth in Figure A1 (right). This makes sense as there are only two observations for $T = 2$, and therefore the maximum and minimum value will always be one of those values.

The results of this analysis show that the main differences are absolute shifts, rather than relative shifts in the scores. Nevertheless the use of $T = 15$ while retaining the delta flow term gives more pronounced results, as the absolute values are higher. A more pronounced result makes it easier to

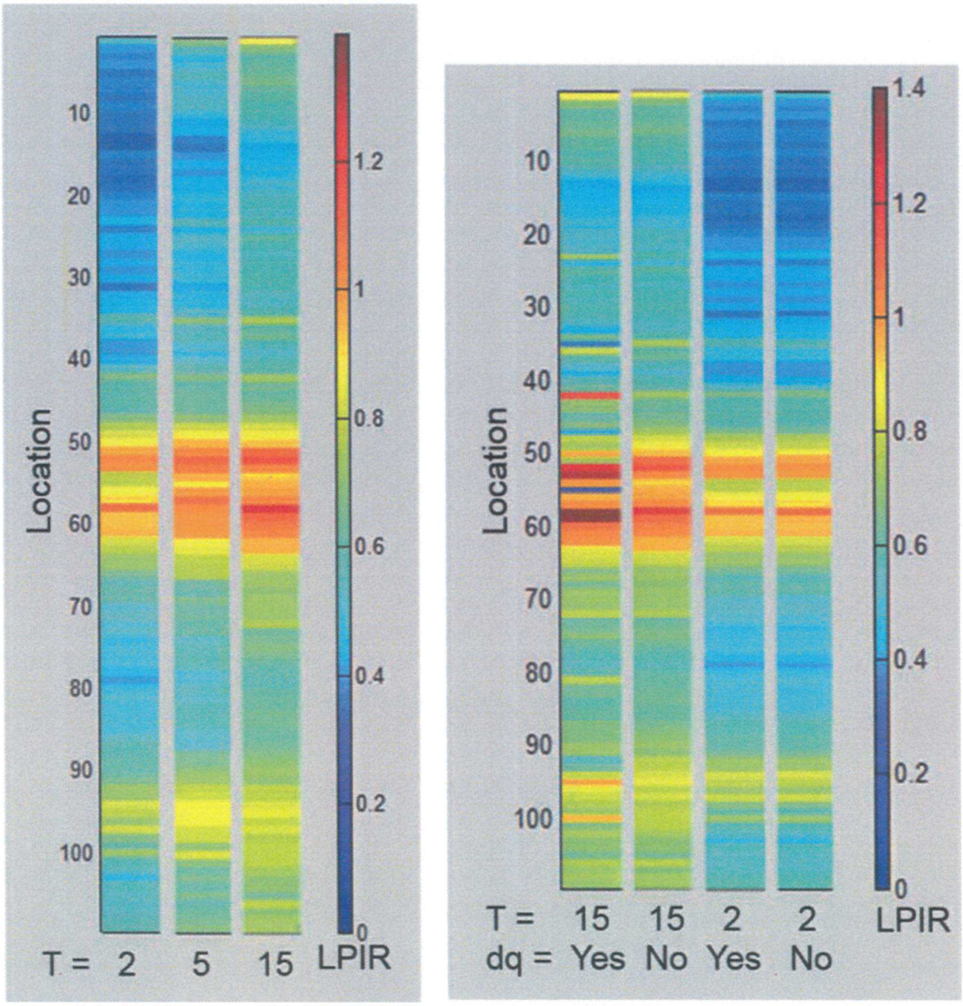

Figure A1. (Left) comparison between time interval values, from left to right: 5, 15, and 2 min. (Right) comparison between time interval values and the application of delta flow, from left to right: $T = 15$ min with Δq, 15 min without Δq, 2 min with Δq and 2 min without Δq.

distinguish between roads sections and therefore a preference is made to use a $T = 15$, with the delta flow term. This also gives more observations to make an estimate of the volatility, which is limited by a smaller T value. While stating this, we recognise that the use of a lower T value would not necessarily be an incorrect approach.