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# Assessment of Non- Recurrent Congestion on Dutch Motorways

Camilo Medina

September 2010



Rijkswaterstaat

 **TU Delft**



# Assessment of Non- Recurrent Congestion on Dutch Motorways

Camilo Medina

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Final Report

**MSc Thesis Civil Engineering  
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## Colophon

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## Preface

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The beginning of this report is that Rijkswaterstaat misses a tool to accurately assess the different parts of the congestion in the Netherlands. It led them to propose this topic to the ITS Edulab, which is a cooperation between the Rijkswaterstaat Centre for Transport & Navigation and the Department of Transport & Planning of the faculty of Civil Engineering & Geosciences at the Delft University of Technology. As a student of the latter, I found interesting to research in this topic, which is developed as my graduation project that is part of the requirements to obtain my Master degree in Transport, Infrastructure, & Logistics.

The main purpose of this report is to present the results of the research made and the methodology developed, as the answer of the original Rijkswaterstaat requirement.

Clearly, this report could not come into being without the collaboration and supervision of the members of the evaluation committee. They were always intending to improve the quality of the research process in order to obtain the desired outcomes. For this reason I am grateful to them for their time and commitment in the development of the project. I would like to extend special thanks to Winnie Daamen, for her time and dedication during this time.

Thanks to God for the inspiration. I cannot develop this project with the continuous support and love of my family overseas: my father, my brother, my sister, and above all my mother. I would like to dedicate this research to them. Gracias por apoyarme siempre y en toda circunstancia.

Camilo Medina  
Delft, September 2010.

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## Summary

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Congestion is a problem that nowadays is facing people all over the world. It affects (in different degrees) developed countries as well as undeveloped. Congestion and queues on freeways cost money due to loss of time and therefore productivity. As a result it is considered important to assess it, in order to determine the severity of the problem faced. In the case of the Netherlands, a clear and accurate review of the causes of congestion and their contribution to vehicle loss hours is missing. For that reason, Rijkswaterstaat [RWS] proposes to investigate this topic.

As a result, the main matter of this project is to differentiate diverse types of congestion. Hence the main research objective is to design a method to automatically identify the recurrent and (the most common) non-recurrent delays during single occurrences, on Dutch motorways.

To achieve this objective the research question is posed: "Which part of single event delays on the Dutch motorways is caused by the following non-recurrent elements: roadworks, incidents, and adverse weather conditions?". Besides that, the intention is to answer a set of sub-questions and sub researching objectives, which are naturally related with the main research question.

To accomplish these goals, it was necessary first to have a clear definition of congestion, which in this study was used travelling below a reference speed. It is also required to have a clear differentiation between recurrent and non-recurrent congestion. These are the elements that will be measured in this report.

Reviewing the existing methodologies to assess different congestion, it was found that exist two main approaches to assess different congestion components: simulation-based and data driven. They both were examined in order to determine which would be the most suitable approach to be used in this study. Taking into account several factors, it was decided that the most promising approach is data-driven, and thus it is the used in this report.

During the checking process it was noticed some gaps in the existing methodologies to assess congestion, which are: explicit assessment of various causes of non-recurrent congestion, possibility to add in the model new causes of non-recurring congestion, different to those originally considered, lack of a structured methodology, and lack of considering network effects. Hence the new proposal fills all these gaps.

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Bearing in mind these facts and based on the existing methodologies, a new method was proposed to assess and to distinguish the different parts of the congestion: recurrent and non-recurrent, expressed in terms of delays. Given that the data collection process in the Netherlands uses inductor loop sensors spaced approximately 500 m, then the input data are speeds and flows measured by these sensors per motorway sections (space between these detectors) aggregated every 5 min. The remaining inputs are network configuration and databases containing time and locations of the mentioned non-recurrent events. The outputs are the delays, classified in total, recurrent, non-recurrent with known and unknown (other) causes. The methodology was validated to show that its outcomes are realistic, and they are properly measuring the field conditions.

The methodology was applied to a case study with real data. It was chosen a zone in the Randstad area including the A4, A13, A20, and A12 motorways in the Netherlands. The resulting delays data were analyzed and some conclusions were derived from the case study. It was found that in this area the A13 and the A20 present the higher congestion levels. It was also found that recurrent delays represent more than 50% of the total delays and among the considered causes of non-recurrent congestion, incidents is the one that occur more often.

In addition to the goal of measuring non-recurrent delays, it was also considered the existing policies and measures created in the Netherlands to handle them. It was found that they are the result of several years of investments and developments. Therefore, the existing policies and measures to tackle non-recurrent congestion (mainly Incidents Management IM and roadworks planning) have high quality. Nevertheless it is considered that it is required further integration of the above mentioned measures with ITS services, in terms of traffic management measures and an extensive use of the providing information services. The last is especially evident in handling adverse weather conditions, as one of the considered sources of non-recurrent congestion.

It was found in the results of non-recurrent delays classified as 'other causes' are higher than expected. Part of it is originated in bottlenecks whose cause is not among the databases. Therefore it is considered that although the quality of the existing information is high, it is still necessary more information about different kinds of occurrences, different from those considered in this study.

The case study results are promising, however the developed methodology requires more data (in more motorways and considering more time) in order to derive more generic conclusions.

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# 1. Introduction

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Congestion on freeways is a growing problem that nowadays can be seen all over the world. It occurs when the vehicle demand exceeds the available capacity (Bovy, 2001). Congestion and queues on freeways cost money due to loss of time and therefore productivity (Koopmans & Kroes, 2003). According to the Kennisinstituut voor Mobiliteitsbeleid [KiM] (2009), the estimated external costs per year in the Netherlands related to road traffic are:

- €2 billion to €8.5 billion attributable to environmental damage.
- €10.4 billion to €13.6 billion due to traffic accidents.
- €2.8 billion to €3.6 billion imputable to congestion and delays.

Consequently the total external costs for society related to traffic per year are between €15 billion and €26 billion.

Currently, there are several approaches for defining and measuring congestion delay. Nevertheless, there is a lack of consistent definition and measurement of the congestion and the parts that it consists of, using real-world data (Skabardonis, Varaiya, & Petty, 2003). Also in the Netherlands, a clear and accurate review of the numerous causes of congestion and their contribution to vehicle loss hours is missing. For that reason, Rijkswaterstaat [RWS] proposes to investigate this topic. The final objective of RWS is to have an improved method that supports the estimation of the delays on freeways (including its different causes), which are the base of the recommendations presented on information panels. In the short term, the objective is to develop a robust method for statistical purposes. As a result, to identify and quantify the main congestion components on Dutch motorways is the main aim of this thesis project, which will be carried out at the ITS-Edulab.

This chapter begins providing background information about the problem (problem definition), which leads to the research objective and research questions. Some points are then presented that are not included in the research (research boundaries), and the chapter is finalizing with the research approach and report outline.

## 1.1 Problem Definition

The Verkeerscentrum Nederland [VCNL] and the Dienst Verkeer en Scheepvaart [DVS] of RWS are currently insufficiently able to indicate which part of the congestion is due to demand exceeding capacity in regular conditions (recurrent congestion), and which part is caused by external additional (non-recurrent) elements. Currently, RWS determines these parts of congestion based on best practice and

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experience. According to RWS, which matches with the findings of Skabardonis et al. (2003) and Kwon, Mauch & Varaiya (2006), the additional (non-recurrent) delay is mainly caused by incidents (such as accidents and breakdowns), roadworks, and other random events, such as inclement weather. Most of the non-recurrent congestion problems originate in this kind of occurrences that decrease the available capacity of the roads, but capacity reductions also originated in changes in driving behavior on both the remaining and other direction lanes (Knoop, 2009).

In this report, the considered non-recurrent causes of congestion are grouped in four categories: roadworks, incidents (e.g. accidents), adverse weather conditions, and network effects. In the first two categories (roadworks and incidents) there is a physical effect that reduces the capacity supply due to lane blockages and causing congestion. In these cases a bottleneck is observable, being the roadworks "planned" while the incidents are intrinsically "random". Meanwhile, in the third category there is a non-physical effect: it leads to changes in driving behavior and as a result a capacity decrease. As an example, under adverse weather conditions there is no "bottleneck" and its effects are experienced over a number of road network segments.

It also has to be considered that there is no linear relationship between capacity reduction and flow decrease. It has been demonstrated that the flow on motorways reduces more than the reduction in capacity. For instance, Knoop (2009) found that during incidents on Dutch motorways the capacity per lane (both in the same and opposite direction) reduces significantly due to a change in driving behavior and the size of this reduction depends on the incident severity. For instance, if one of the driving lanes is blocked, which means 33% of capacity reduction when 2 out of 3 lanes are blocked, the remaining lanes are used 46% less efficient, which yields an "efficiency factor" of 54% (Knoop, 2009).

Regarding adverse weather conditions, the state-of-the-art related to weather impact studies on traffic is relatively sparse (El Faouzi, de Mouzon, & Billot, 2008). The weather conditions affect the driving behavior, which may reduce the road throughput (traffic flow), and as a result potentially lead to congestion. For example, El Faouzi et al. (2008) found that under similar demand conditions, the rain impacts drivers' behavior by reducing the speed and increasing time headways and spacing.

The consequences of congestion are mainly delays (time loss) and queues. A better understanding of them can improve for instance the traffic state prediction and thereby may improve Traffic Management measures (Knoop, 2009). The congestion in this project is measured in terms of delays caused by non-recurrent factors mentioned above. The expected value of the total delay can be decomposed into recurrent and non-recurrent delay, as stated by Skabardonis et al. (2003). It

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means that this phenomenon follows the superposition principle and the total congestion could be obtained as a sum of the different components. In the same manner, Skabardonis et al. (2003) assert that the non-recurrent congestion is the sum of the congestion from accidents and non-accident incidents.

When these non-recurrent elements are present, they may affect some drivers' choices such as route, departure time, and destination, among other things. Therefore, it is necessary to look in a broader extent than in a road stretch to assess the impacts that those occurrences have over the network. For that reason, potential flows divert to alternative routes when these non-recurrent elements are present, are going to be studied as well, the so-called network affects.

Based on all of the above, it is possible to identify and to state the problem definition, as follows.

.....  
Problem Definition

The main matter of the project is to differentiate diverse types of congestion. Hence the main research objective is to design a method to automatically identify the recurrent and (the most common) non-recurrent delays during single occurrences, on Dutch motorways.

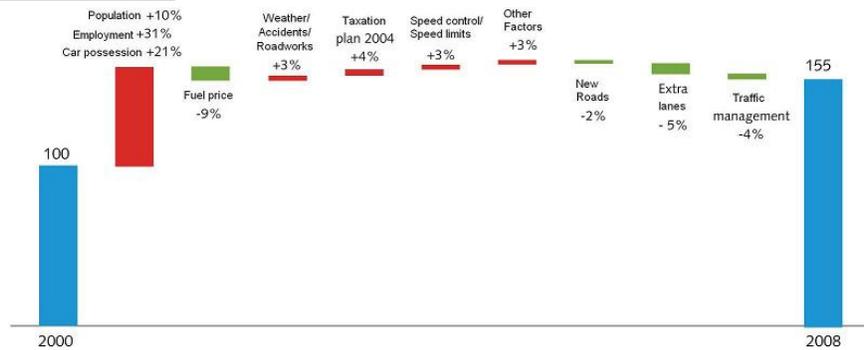
### **1.1.1 Current delays situation in the Netherlands**

Nowadays, both recurrent and non-recurrent congestion (measured in terms of delay) in the Netherlands are measured via linear regression (MuConsult, 2006). This linear regression is based on one-year aggregated data. The explanatory variables include both increase and decrease factors of congestion (MuConsult, 2006), being: external factors (i.e. population increase, employment), traffic management measures (i.e. congestion lanes, dynamic route information panel DRIP, construction new infrastructure), accidents, roadworks, weather conditions, and fuel costs. As it may be seen, the non-recurrent causes of congestion are explicitly considered within the model. However, the aggregation level of the data is broad (year) and the reliability of the values presented is unknown. Obviously, the intention of this study is to enhance the accuracy of this calculation process, using better data and methodology. The results of the mentioned study are used for statistical purposes, especially evolution of the variables through years. They are included here as initial reference values.

#### **Extent of Congestion**

Based on this model, the Kennisinstituut voor Mobiliteitsbeleid [KiM] (2010) analyzed the evolution of congestion in the Netherlands in the period between 2000 and 2008. The result is presented in Figure 1.1, in which the reference of congestion levels (100%) are those presented in the year 2000, and the rest of the numbers represents the shares in the total change (regarding to the reference year).

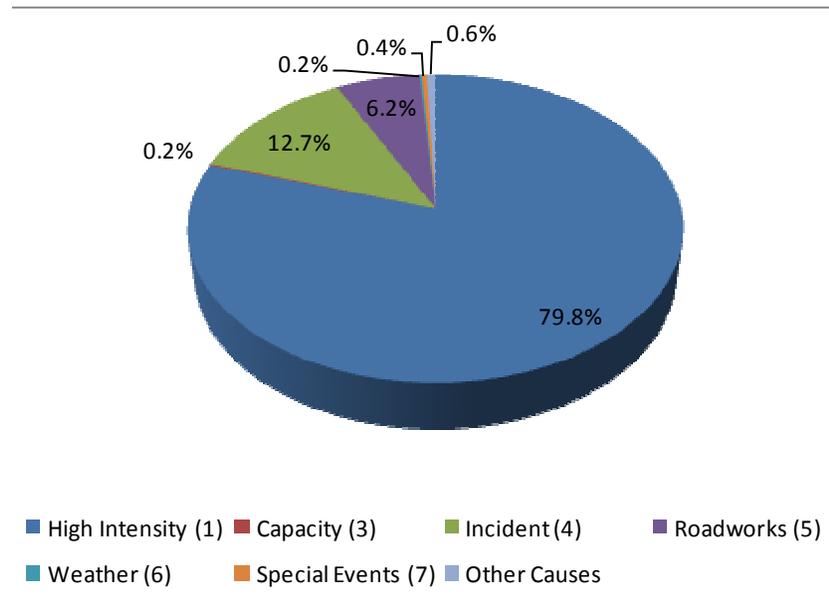
.....  
**Figure 1.1:** Account of increase in delays in the main road network (with respect to reference speed 100 km/h) (KiM, 2010).



In Figure 1.1 it may be seen that in the period analyzed, congestion (delays) has increased with 55%<sup>1</sup>. Factors that increase congestion level the most are those considered above as external (population increase, employment, and car possession), which are difficult to control. In the same manner, fuel prices have the highest share in reducing congestion (-9%), even more than new infrastructure (roads and lanes).

The share of the different sources in the total value of congestion in the Netherlands during 2009 is shown in Figure 1.2, obtained from [nis.rijkswaterstaat.nl](http://nis.rijkswaterstaat.nl). The figure shows different causes of congestion explained later on (section 2.2), with the corresponding number in brackets. According to the figure, the main source of congestion in the Netherlands is high intensity (that is fluctuations in Normal Traffic, explained later on), which is a recurrent cause of congestion and accounts for about 80% of the total value. The main non-recurrent causes of congestion are incidents and roadworks, which sum up almost 19% of the total.

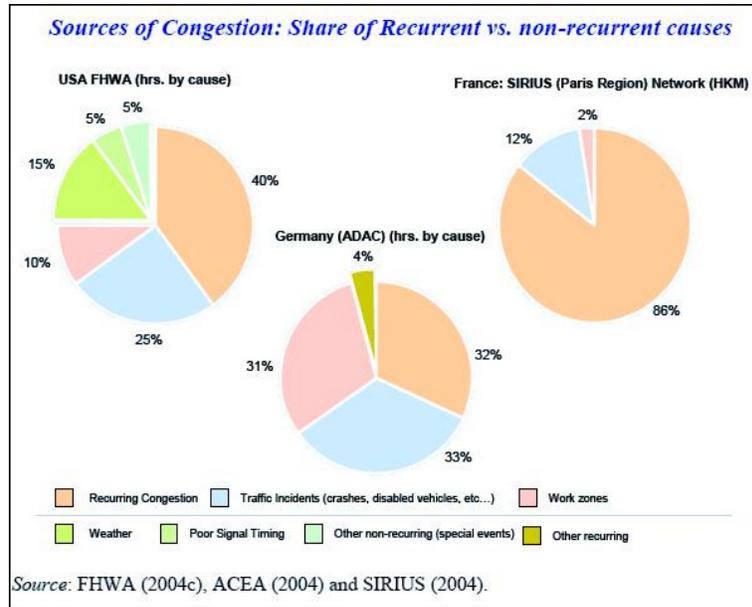
.....  
**Figure 1.2:** Share of different sources of congestion in the Netherlands in 2009 ([nis.rijkswaterstaat.nl](http://nis.rijkswaterstaat.nl)).



<sup>1</sup> It may be arguable the fact that this figure was built with a reference speed of 100 km/h for the whole network, with different speed limits

Looking to the situation in other countries as a reference, makes it possible to compare those values in Figure 1.2. Figure 1.3 contains the share of the causes of congestion (mentioned earlier) in the total value in the United States, France, and Germany, taken from Joint Transport Research Centre [JTRC] (2007).

.....  
**Figure 1.3:** Share of different sources of congestion in some countries (CSI and TTI, 2005).



Based on the figures above, it is possible to assert that meanwhile in the Netherlands the non-recurrent congestion represents about 20% of the total, in the United States 55%, in France 14%, and Germany 64%. Of course these values depend on many factors, and as it was mentioned above, they are only used as a reference. The variation among these countries is high, however the value in The Netherlands is comparable with that reported in France.

## 1.2 Research Questions and Objectives

The problem requirements indicated primarily by VCNL and DVS (which in this proposal are considered the problem owners) lead to the following research question:

.....  
 Main research question:

“Which part of single event delays on the Dutch motorways is caused by the following non-recurrent elements: roadworks, incidents, and adverse weather conditions?”

Besides that, the following research sub-questions and design sub-objectives are stated:

1. How to match in time and space the information of the different data sources e.g. accidents (time and location) with congestion occurred?
2. Design a method to identify quantitatively the different parts of the congestion and apply it to a case study.

- 
3. How is diverted the traffic flow in the network when the non-recurrent elements are present?
  4. Which percentage of the total delays is produced by non-recurrent causes?
  5. What is causing most of the non-recurrent congestion and how could they be tackled?
  6. Make policy recommendations to mitigate the adverse effects of the non-recurrent congestion.

### **1.3 Research Boundaries**

Bearing in mind the constraints (e.g. time horizon to develop this survey), it is necessary to establish some boundaries to this thesis research:

- Only motorways are going to be considered. Therefore neither urban nor minor roads will be taken into account.
- The possible causal relationship between occurrences is not considered. For instance, the relationship between adverse weather conditions and incident rate.
- The objective is not to design a Traffic Management tool. Even though the outcomes could be used with this purpose.

### **1.4 Report Outline**

The research and consequently the report, is set out to accomplish the research objective and answer the research questions. Therefore all of the research parts (and report) are correlated with them. Thus, the way to explain the logic behind the report set up is correlating with the research objective and research questions.

Following the introduction is the Literature Review (Chapter 2), which is correlated with all of the research questions. The literature research aims to both give the background information and identify the missing points in the theories behind the different topics discussed in this study. This is made presenting the basic concepts explaining and classifying congestion and discussing about the effects that congestion may have on the traffic network. In Chapter 3 an overview is given of the current situation of the (non-recurrent) congestion in the Netherlands and in other countries, as well as policies and measures undertaken to tackle it.

Chapter 4 is devoted to explain the methodology to assess the non-recurrent congestion. This process is based on the already existing methods, but the final outcome is a new methodology. This is the main objective of this thesis, and in this chapter also responds to research questions 1 to 3. The chapter begins describing the data collection process followed by the description of the available data sources along with the process of checking data. The final part of the chapter is

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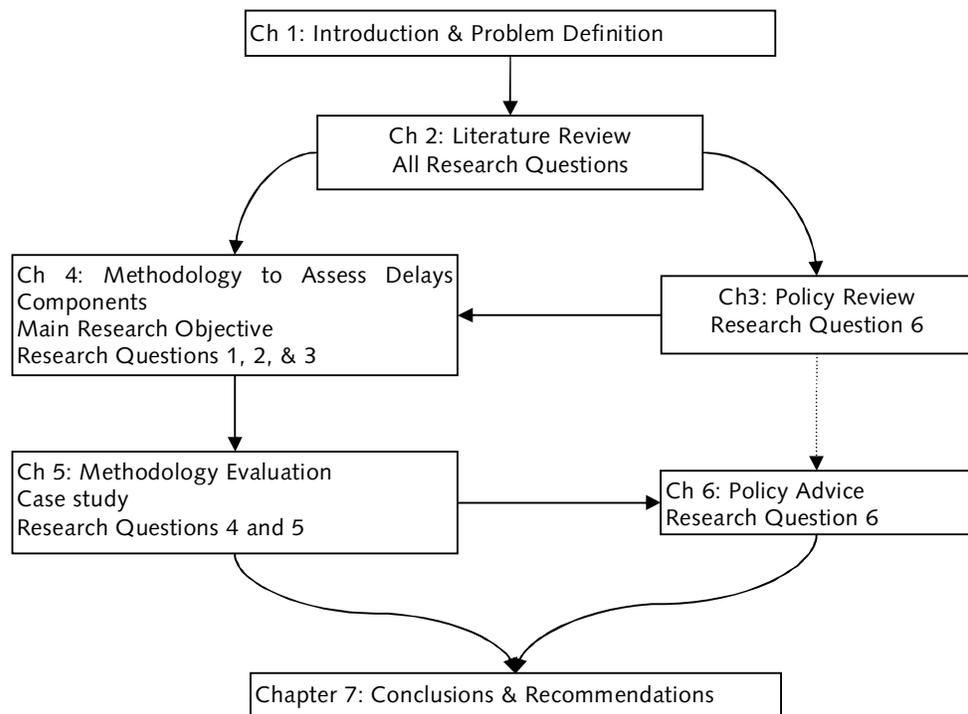
devoted to the methodology itself, explaining in detail all the steps comprised.

This method will be applied in a study area using real data, as is explained in Chapter 5. The purpose of this chapter is to solve Research Questions 4 and 5. After apply the methodology, the results can be aggregated and analyzed, in order to derive conclusions. These results will let us to assess the different causes of congestion and deduce which has the largest impact on the delays. In this way, the policy efforts can be directed to tackle this (these) cause(s) that has the biggest impacts.

Consequently, the results of Chapter 5 are used to give the policy advice of Chapter 6. This is the answer to Research Question 6. It is based on the results of the investigation performed on Chapters 2 and 3.

The final Chapter (7) includes the conclusions and recommendations derived from the study. These are the results of the entire process and summarize the answer to the research objective and research questions. It also includes other recommendations that may arise in the process. The outline of the report could be observed in Figure 1.4.

.....  
**Figure 1.4:** Report Outline



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## 2. Literature Review

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The literature review aims to both give the background information for the research and identify the missing points in the theories behind the different topics discussed in this thesis project. The starting points to select the topics to be included were the research question and sub-questions set out in the previous chapter.

The chapter first presents basic concepts explaining congestion from different perspectives, including the way in which congestion is classified in this study. This is followed by the description about queues and delays and the interaction of the different factors to onset congestion. Then, there is a review of the existing methodologies to assess non-recurrent congestion. Two different approaches exist: simulation-based and data driven. Both approaches are examined and based on criteria selected for this study, a selection of the approach type is made. The next part discusses about the effects that congestion may have on the network. The final part of the chapter presents the conclusions of the literature review.

Due to its character, roadway throughput could be consistent and monotonous, as well as highly variable and unpredictable at the same time. It is consistent and repetitive in that peak periods occur regularly and throughput can be estimated with a degree of reliability. Simultaneously, it is highly variable and unpredictable, in that on any given day, unusual circumstances such as crashes can dramatically change the performance of the roadway, affecting both travel speeds and flows. As a result, it is no longer valid to define congestion in terms of “average” or “typical” conditions. In this point, reliability becomes significant, as it indicates how much events influence traffic conditions, in terms of how travel times vary over time. It is particularly important when it comes to defining operation strategies, which aim to control the effect of these events. Improving the reliability of travel times is significant for a number of reasons such as to improve delays forecast, to save time and fuel, to decrease vehicle emissions, and to lead to safer highways (Cambridge Systematic Inc [CSI] & Texas Transportation Institute [TTI], 2005).

### 2.1 Basic Traffic Flow Theory

Most of the events discussed in this thesis are based on and explained by traffic flow theory. Therefore it is necessary to be familiar with the traffic flow theory concepts, in order to grasp the subjects discussed here. Nevertheless, the description of the majority of those concepts is not included here, as there are many and good literature available about them. In case of requiring further explanations or details, it is recommended to look for instance in Daganzo (1997), Gartner, Messer,

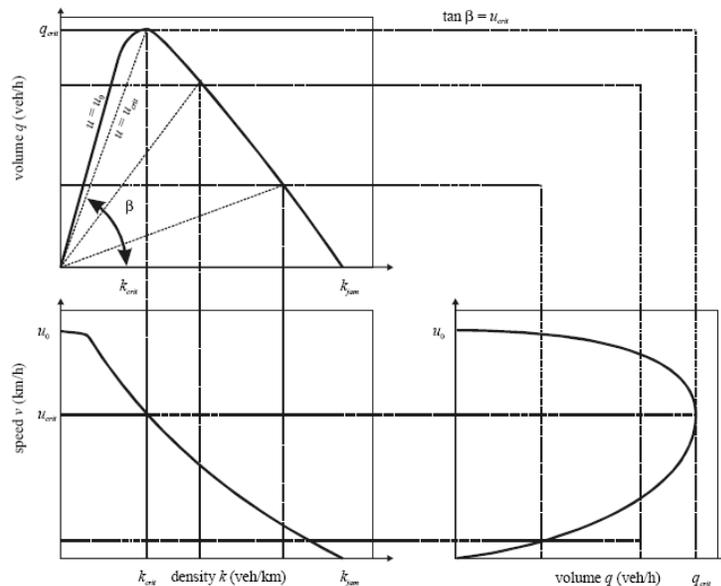
& Rathi (2001), Kerner (2009), Hoogendoorn (2007), or van Lint (2009). The concepts included in this first part of the chapter are then no more than those considered essential, as they are the basis for the developments of the topics that concern this thesis.

In a general way, traffic flow theory seeks to describe in a mathematical way the interactions between vehicles and their drivers (the mobile components) with the infrastructure (the immobile component). The models and tools that are being used in the design and operation of streets and highways are based on these theories (Gartner, Messer, & Rathi, 2001). Traffic flow has to deal with phenomena that are associated with a complex dynamic behavior of spatiotemporal traffic patterns (Kerner, 2009). As the main subject that matters in this research is congestion, in the following a review will be made of the traffic flow theory related to congestion.

## 2.2 Congestion

Free flow traffic (free flow for short) is usually observed when the vehicle density in traffic is small enough that the interactions between vehicles are negligible. Therefore, vehicles can move with their desired speeds (subject to traffic regulations). When density increases in free flow, the flow rate increases too, however, vehicle interaction cannot be neglected anymore. As a result of vehicle interaction in free flow, the average vehicle speed decreases with increase in density (Kerner, 2009). It matches with the rising line of the fundamental diagram in the volume–density plane when the slope is positive, as is illustrated in Figure 2.1. This behavior is exhibited until the maximum flow and critical density are reached, corresponding with the points  $q_{crit}$  and  $k_{crit}$  in Figure 2.1.

.....  
**Figure 2.1:** Example Fundamental diagram (Hoogendoorn, 2007)



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Congested traffic is defined as a state of traffic in which the average speed is lower than the minimum average speed that is possible in free flow (Kerner, 2009). It corresponds with the right line of the fundamental diagram in Figure 2.1 (in the volume–density plane, top left of the figure), when the slope is negative. The maximum possible density is in the jam density  $k_{jam}$ , when there is no flow ( $q = 0$ ) and all the vehicles are standing still.

In contrast, in a broader (and less technical) sense, congestion can be defined as excess of vehicles (compared with road capacity) on a section of roadway at a particular time moment, resulting in speeds that are lower than normal or free flow speeds. Congestion often means stopped or stop-and-go traffic (CSI & TTI, 2005). As it was mentioned before, congestion leads to delays and queues. From now onwards, congestion will be measured in terms of delays, with the definition given above.

Congestion (delays) can be divided into recurrent and non-recurrent congestion (delays). For instance, Gordon & Tighe (2005) define that congestion commonly expected at predictable locations during approximately predictable periods of time is named recurrent congestion, as these present during weekdays in the commute periods. In contrast, other forms of congestion result from random or less predictable events, and it is called *non-recurrent congestion*. The most common cause of non-recurrent congestion is accidents (Gordon & Tighe, 2005).

Hallenbeck, Ishimaru, & Nee (2003) describe recurring congestion as congestion caused by routine traffic volumes operating in a typical environment. It might be thought of as “the congestion present on a normal day if no incidents have happened on the roadway.” “Non-recurring congestion” is defined as “unexpected or unusual congestion caused by an event that was unexpected and transient relative to other similar days.” Non-recurring congestion can be caused by a variety of factors.

As it may be seen, the definitions above match approximately between them and also with those given by Kwon, Mauch, & Varaiya (2006); Skabardonis et al. (2003); Recker, Chung, & Golob (2005); and Hall (1993). These mentioned authors have developed methodologies to obtain non-recurrent congestion, which will be discussed later on. It is noticeable that all of them are underlain by the same hypothesis, which is only explicitly stated and demonstrated in Skabardonis et al. (2003). This hypothesis is that the delays follow the superposition principle, i.e. delays can be obtained as the sum of different components, as follows:

.....  
Equation 2.1

$$E[D(s,t)] = \text{Recurrent congestion} + \text{Non-recurrent congestion}$$

Where  $E[D(s,t)]$  is the expected value of the delay section  $s$  over a time period  $t$ . This fact is important since determining the various components of delay and summing them up, makes it possible to

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obtain the total delays, which is one of the basic theories used in this study. The reason to use expected value is that the delay has a random nature and therefore its magnitude requires a statistical characterization, which may imply statistical mean, variance, quartiles, and probability distributions.

All of the mentioned authors include the causes of non-recurrent congestion in their definitions, although in different words, but they are basically the same. For instance, Hallenbeck et al. (2003) consider among causes of non-recurrent congestion lane blocking accidents and disabled vehicles, other lane blocking events (e.g., debris on the roadway), construction lane closures, and inclement weather. Kwon et al. (2006) decompose (total) congestion in six causes: incidents, special events, lane closures, adverse weather, congestion that can be eliminated by ideal ramp metering, and residual delay (largely caused by demand that exceeds the maximum sustainable flow). Recker et al. (2005) only consider accidents and Hall (1993) only contemplates incidents. Hallenbeck et al. (2003) also mention some causes of congestion not referred to in other sources, as significant roadside distractions that alter driver behavior (e.g., roadside construction, electronic signs, a fire beside the freeway), heavier than normal vehicle merging movements, and significant increases in traffic volume in comparison to "normal" traffic volumes. The last one is considered especially important, as it could be attributable to traffic diverted from other roads (for multiple reasons) as a consequence of non-recurrent events, which are called 'networks effects' later on in this thesis.

Besides, the CSI and TTI (2005) report provides a snapshot of congestion in the United States, rather than a methodology to measure non-recurrent congestion. However, it decomposes congestion into seven causes, giving a good, broad and structured frame of reference.

All the mentioned sources were assessed and after grouping similar terms, it was concluded that the causes of congestion that will be used in this study are those presented in the following section. They are classified into recurrent and non-recurrent causes of congestion.

### **2.2.1 Recurrent Causes of congestion**

As explained above, the recurrent causes of congestion are the following:

1. Fluctuations in Normal Traffic: Day-to-day variability in demand leads to some days with higher traffic volumes than others. If traffic demand exceeds the fixed capacity of the system, longer (unreliable) travel times are the result.
2. Traffic Appliances: Intermittent disruptions of traffic flow by control devices such as railroad grade crossings, lifting bridges, and poorly timed signals also contribute to congestion and travel time variability.

- 
3. Physical Bottlenecks (“Capacity”): Capacity is determined by a number of factors: the number and width of lanes and shoulders; merge areas at interchanges; and roadway alignment (grades and curves). It is also influenced by a highly uncertain factor: driver behavior. All these factors lead to variations in the amount of traffic that can be handled.

### **2.2.2 Non-Recurrent Causes of congestion**

The causes of non-recurrent congestion are:

4. Traffic Incidents: These are events that disrupt the normal flow of traffic, usually by physical impedance of the travel lanes. Events such as vehicular crashes, breakdowns, and debris on travel lanes are the most common form of incidents. Furthermore, Knoop (2009) showed that those incidents have an additional influence (apart from the physical effect) on the driver behavior, not only on the incident direction, but also in the opposite direction, affecting the traffic flow.
5. Roadworks: These are the construction activities on the roadway that result in physical changes to the highway environment. These changes may include a reduction in the number or width of lanes, lane shifts, lane diversions, reduction, or elimination of shoulders, reduction in available number of lanes and even temporary roadway closures.
6. Weather: Environmental conditions can lead to changes in driver behavior that affect traffic flow. Due to reduced visibility, drivers will usually lower their speeds and increase their headways when precipitation, bright sunlight on the horizon, fog, or smoke are present. Wet, snowy, or icy roadway surface conditions will also lead to the same effect even after precipitation has ended.
7. Special Events: Traffic demand patterns are radically different from typical ones in the vicinity of special events (e.g. sport games, concerts, etc.). Special events occasionally cause surges in traffic demand that may overwhelm the system. Even special occasions as evacuations are within this category.

In addition to the mentioned seven causes of congestion, it would be congestion that arises in other roads in the transport network, which are referred to as ‘network effects’ in this document. That means that a congested link may spill back the congestion to the upstream links. Therefore, there are significant increases in traffic volume in comparison to “normal” traffic volumes in those links upstream, attributable to traffic diverted from other roads (for multiple reasons). However, it cannot be considered as a separate cause of congestion, as it is the consequence of one (or more) occurrence mentioned above. Nevertheless, these effects will be analyzed in this report.

In Rijkswaterstaat [RWS] (2007) it could be seen that the main causes of non-recurrent congestion in the Netherlands are traffic incidents, roadworks, and weather conditions. Comparing with the causes given above, it is noticed that special events are not included. As will be observed later on, causes that have information available are those that could be measured, and it is not the case for special events.

As it was noticed, the congestion sources Traffic Incidents (4) and Roadworks (5) have a (mainly) physical effect that impedes or blocks part of the infrastructure and often a bottleneck is detectable. Whereas congestion source Weather (6) has impacts mostly on driving behavior.

However, impacts of traffic incidents on road capacity are not only limited to lane blockage. Knoop (2009) made a detailed study with a microscopic approach and using real-life traffic data taken from a helicopter during incidents in Dutch motorways. He concluded that during traffic incidents, the total road capacity decrease is larger than physical infrastructure supply reduction caused by lane blockages. This is a result in a shift of drivers' attention, which leads to different driving behavior. Particularly, Knoop (2009) demonstrated that:

- Drivers choose a different headway in a bottleneck caused by an incident compared to a bottleneck in normal traffic and the mean headway is larger,
- Drivers have larger reaction times at an incident compared to normal conditions,
- Drivers reduce speed in view of an accident,
- Queue discharge rate at the incident is lower than the outflow capacity under normal conditions for the same roadway geometry, and this is not due to the capacity drop. This may be due to the "rubbernecking effect", this is the fact that drivers are distracted watching what is happening.

These facts appear also in a more quantitative manner in the Highway Capacity Manual [HCM] 2000 (Transportation Research Board [TRB], 2000). Table 2.1 shows the share of the road segment capacity available under incident conditions. There could be seen for instance that a road with 2 lanes and one lane blocked, the remaining capacity is 35% of the original (instead of 50%).

.....  
**Table 2.1: Share of the road segment capacity available under incident (TRB, 2000)**

| <b>Number of freeway lanes by direction</b> | <b>Shoulder disablement</b> | <b>Shoulder accident</b> | <b>One lane blocked</b> | <b>Two lanes blocked</b> | <b>Three lanes blocked</b> |
|---|-----------------------------|--------------------------|-------------------------|--------------------------|----------------------------|
| 2   | 0.95                        | 0.81                     | 0.35                    | 0.00                     | N/A                        |
| 3   | 0.99                        | 0.83                     | 0.49                    | 0.17                     | 0.00                       |
| 4   | 0.99                        | 0.85                     | 0.58                    | 0.25                     | 0.13                       |
| 5   | 0.99                        | 0.87                     | 0.65                    | 0.40                     | 0.20                       |
| 6   | 0.99                        | 0.89                     | 0.71                    | 0.50                     | 0.26                       |
| 7   | 0.99                        | 0.91                     | 0.75                    | 0.57                     | 0.36                       |
| 8   | 0.99                        | 0.93                     | 0.78                    | 0.63                     | 0.41                       |

Weather conditions influence driving behavior and therefore traffic flow. El Faouzi, Billot, Nurmi, & Nowotny (2010) drove a wide review of the literature related to adverse weather impact on traffic operations at a more aggregated level, looking at the state-of-the-art in several countries. First, they studied changes in traffic demand under adverse weather conditions (macroscopic level). Second, they looked at the effects of weather on the microscopic variables. The main conclusions are summarized in Table 2.2. It is clear that the arrow upwards means an increase in the variable and an arrow downwards a decrease.

.....  
**Table 2.2: Effects of weather conditions on traffic operations (El Faouzi et al., 2010)**

|   |                        |   |
|---|------------------------|---|
| Driver's Behavior<br>(Microscopic level)  | Speed and acceleration | ↘ |
|   | Time headway (h)       | ↗ |
|   | Distance headway (s)   | ↗ |
| Traffic Operations<br>(Macroscopic level) | Capacity (qc)          | ↘ |
|   | Flow (q)               | ↘ |
|   | Speed (u)              | ↘ |
|   | Speed variation        | ↗ |
|   | Congestion severity    | ↗ |

### 2.2.3 Queues and Delays

The main consequences of congestion are delays and queues. On the one hand, delays are defined as the excess vehicle-hours traveled below a reference speed (Skabardonis et al., 2003). On the other hand, queues are (mainly) associated with bottlenecks, where the vehicle demand exceeds the capacity (supply). It is clear that queues always generate delays, but this relationship does not necessarily always hold in the other way around. In queues there is a spillback of traffic on the mainstream, which regularly results in stop-and-go traffic. These vehicles can be considered to be in a queue, waiting their turn to be served by the bottleneck downstream (Hall, 2001).

Based on the definition above, delays  $l$  for a single driver can be calculated as (Knoop, 2009):

.....  
**Equation 2.2**

$$l = \frac{v_f - v_c}{v_f} t$$

Where:  $v_f$ : Reference (free flow) speed  
 $v_c$ : Congestion speed  
 $t$ : Time period analyzed

Hence, the total delay  $D$  for all the drivers in the period considered, can be obtained by multiplying Equation 2.2 by the number of drivers in the analyzed area:

.....  
**Equation 2.3**

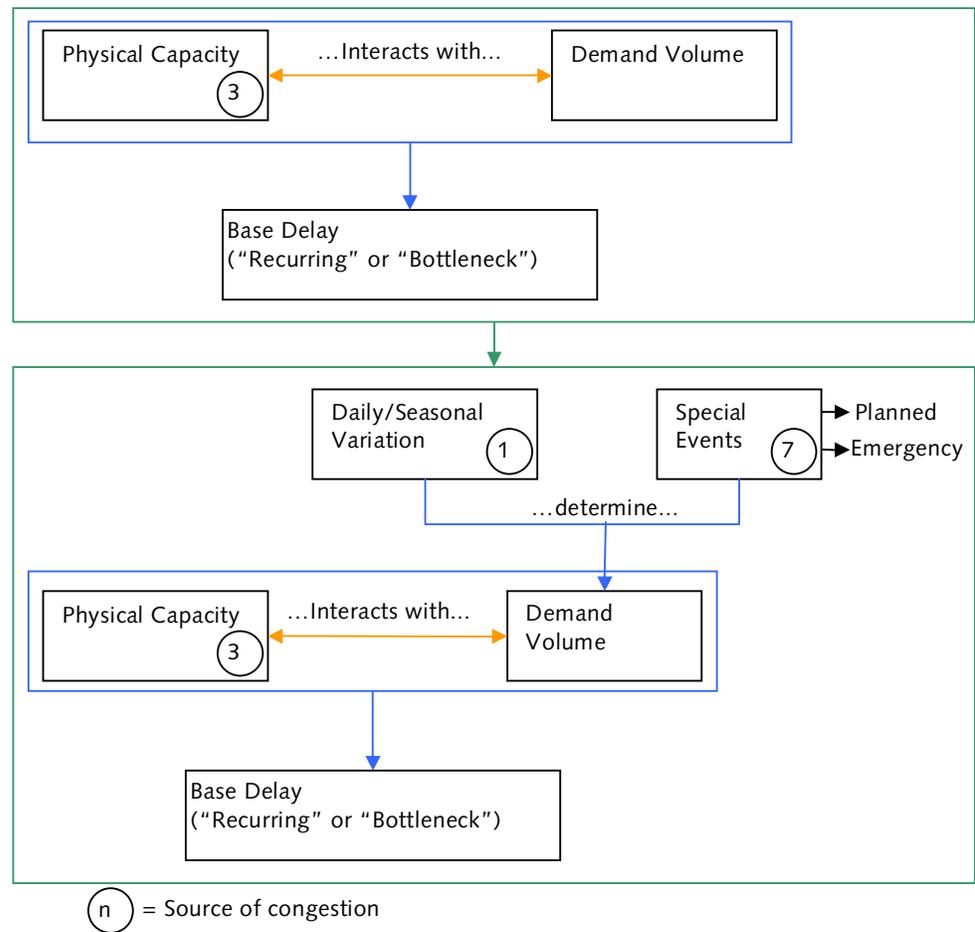
$$D = N(t) \frac{v_f - v_c}{v_f} t$$

Equation 2.3 is the base to compute delays in this thesis, which will be presented later on.

## 2.2.4 Onset of Congestion

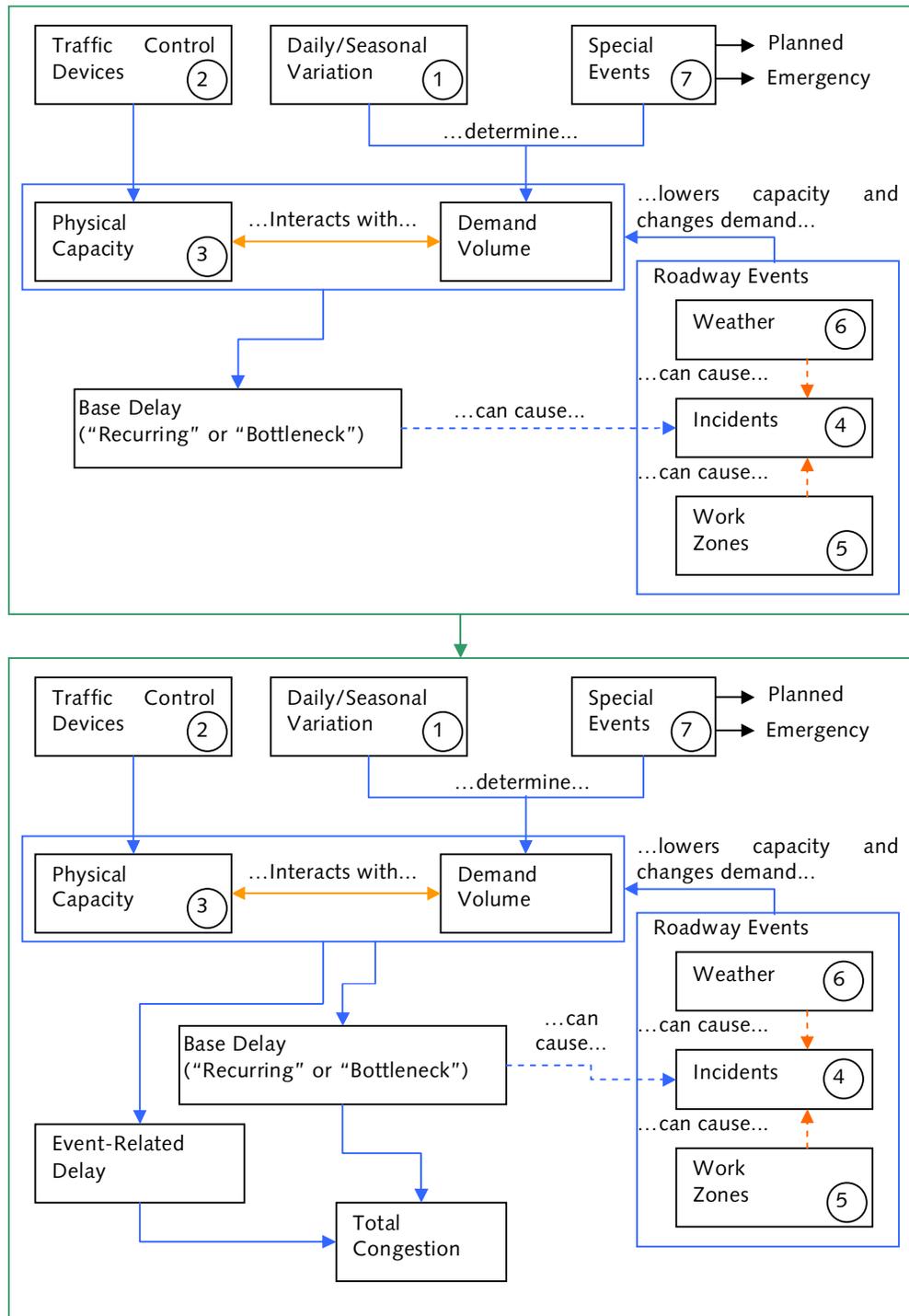
The causes of congestion mentioned above interact among them and with external factors such as demand volume, as is explained in Figure 2.2 and Figure 2.3. The result of these interactions explains the way in which the congestion is triggered, in the process called by CSI and TTI (2005) 'anatomy of congestion'. It has to be noticed that the numbers on the lower right corner of the boxes correspond with the above mentioned causes of congestion. From the figures it could be derived that the sources of congestion can be tightly interconnected. Based on this, it could be expected that treating one of these sources, has an influence of that source on total congestion plus a partial impact on others (CSI and TTI, 2005).

Figure 2.2: Anatomy of congestion. Traffic volumes interact with physical capacity to produce "Base Delay" (CSI and TTI, 2005)



Particularly Figure 2.2 explains how the recurrent (base) delays are built up, whereas Figure 2.3 includes the interaction of the mentioned non-recurrent causes of congestion, and how both together form total delay.

Figure 2.3: Anatomy of congestion. Roadway events reduce available capacity and add extra delay to the system (CSI and TTI, 2005)



(n) = Source of congestion

### 2.3 Existing Methodologies to Determine Non-Recurrent Congestion

The information presented so far is useful to understand the causes related to both recurrent and non-recurrent congestion. Based on this

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information it is possible to explore the methods developed to assess the non-recurrent congestion.

In order to assess congestion first it is necessary to identify the general conditions of the traffic, which includes basically the variables described in the basic traffic flow theory section. Based on that, it is possible to differentiate the diverse states of traffic, including congestion. Broadly speaking, traffic state estimation approaches (both prediction and calculation) have the following general structure (van Lint, 2009):

.....  
Equation 2.4

$$TC(\geq t) = F(Data(<t), Assumptions \& Parameters) + uncertainty$$

Where TC stands for traffic conditions, F depicts traffic model used and "Data" reflects the inputs to this model in time  $t$  before the analysis period. Uncertainty reflects all the assumptions, simplifications and even ignorance of the phenomenon studied. Equation 2.4 is particularly important in this study since it is part of the evaluation criteria of the methods to calculate non-recurrent congestion, as will be presented later on.

In addition, van Lint (2009) mentions that in literature there are two main streams of approaches that handle traffic estimation problems:

1. Simulation-based approaches use traffic simulation models with or without route/departure time choice
2. Heuristic, data driven approaches are time series or regression based (e.g. neural networks) or a combination of both.

Although using different terms, Calvert (2009) has a similar classification. On his literature review, he found that there are two main categories in modeling traffic flows (demand side): exploratory and explanatory. Exploratory simulation-based approaches are based on the principles of traffic flow theory. Meanwhile, explorative methods (heuristic, data driven approaches) are based on statistical analyses of real data and do not rely on strong theoretical bases for the modeling of processes. The latter are further divided into parametric and non-parametric methods. The term parametric refers to the assumption of a specific functional form for the dependent and independent variables used in the model. Versteegt & Tampère (2003) use the same classification those presented above, naming the categories as explanatory models (Simulation-based approaches) and extrapolation methods (heuristic, data driven approaches).

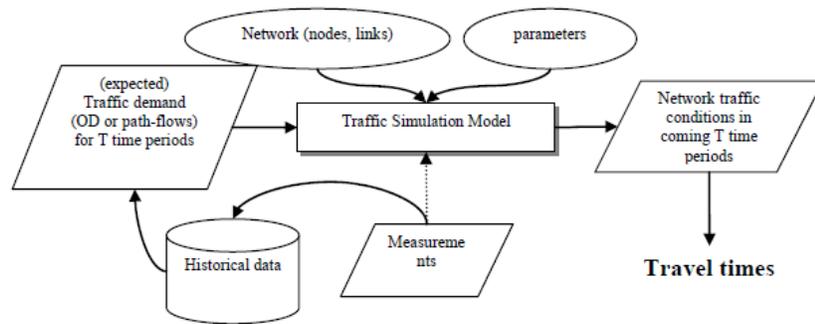
In order to present the methods to calculate non-recurrent delays in this study, they will be split into these two categories: simulation based approaches and data driven approaches.

### 2.3.1 Simulation-based approaches

In these approaches, conditions on the network (or route/link) are estimated with a traffic flow simulation model for a time period from

the prediction time onwards. The general structure of the type of models can be seen in Figure 2.4 (van Lint, 2009).

Figure 2.4: Schematic outline of simulation-based traffic models (van Lint, 2009).



In the figure above it can be seen that the inputs for these models are the network (configuration) with its nodes and links and parameters (features such as link capacities). The other inputs are the historical data (database fed by measurements) from which the expected traffic demand can be derived. Having this information, the model outcome is the estimation of the traffic conditions in the network. In the case of van Lint (2009) the variables of interest were travel times and in this study the variables of interest are congestion and delays.

Based on the structure presented above, it has to be noticed that virtually any simulation-based model (for instance any commercially available traffic simulation software) may represent any network and obtain a result for non-recurrent congestion (simply modeling any situation with and without any non-recurrent occurrence). This model can range from a microscopic simulator (AIMSUN, PARAMICS, MiOS), to a macroscopic model (Fastlane, METANET, DSMART) or even a traffic assignment model with a rudimentary network loading model (e.g. VISUM, INDY) (van Lint, 2009). Hence, the list of available models could be endless.

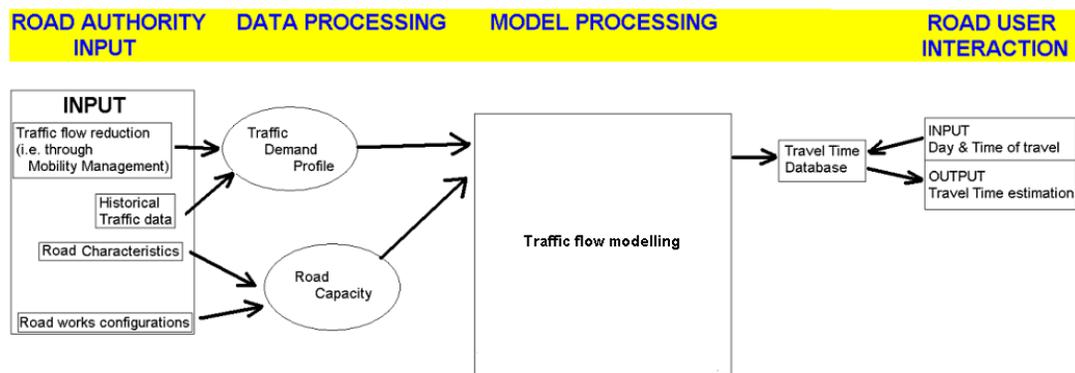
In the same way, it has to be noticed that developing simulation-based models is a time consuming task. Besides, the parameters that require those models (e.g. capacities in regular conditions and bottlenecks, driving behavior, OD matrices, et cetera) are not easy to determine and they can be either obtained from measurements that often need huge amounts of resources (measurement technology, trained personnel, money, etc) or be based on assumptions about the behavior of the traffic system.

This section is focused on those methods that calculate non-recurrent congestion. Taking this into account, it is possible to introduce the most representative simulation-based methods to estimate non-recurrent delays.

### 2.3.1.1. Travel time prediction for long-term roadworks (Calvert, 2009)

Calvert's work was concentrated on prediction of travel times under long-term roadworks (cause 5 of non-recurrent congestion in section 2.2). This model was developed to forecast travel times after considering general traffic conditions gained from information using both historical traffic data and the proposed roadwork characteristics. Travel times are gained by processing a traffic demand profile and a road capacity profile. So, he worked on both sides of the equation: demand and supply. The demand profile was evaluated using historical traffic information and the supply through roadwork configurations, to obtain operational capacities adjusted for the influence of roadworks. The general outline of the algorithm developed by Calvert is shown in Figure 2.5.

Figure 2.5: General model algorithm  
Calvert (2009)



This model was applied using real data. First, Calvert (2009) took major roadworks data in the Netherlands, specifically motorways A2 (major road reconstruction between 2008 and 2009), A9 (major resurfacing works in 2007), and A16 (major bridge repairs between 2006 and 2007) for calibration. The data from construction of additional peak hour lanes on the A12 in 2008 were used for the validation of the model. Taking into consideration the objectives of this survey, the results were concentrated on the accuracy of the model travel time predictions, rather than to typify the delays resulting of the roadworks.

The author found that travel time and consequently (non-recurrent) delays could be predicted for future scenarios by estimating basically capacity and traffic flow, and using the model he developed. For instance, the case study results showed that the predicted travel times during roadworks could be estimated with an error of less than 5% of the recorded travel times at the decisive peak periods.

### 2.3.1.2. Simulating freeways under recurrent congestion (Middleton & Cooner, 1999)

The objectives of this research were to select appropriate models for simulating freeways under recurrent congestion, test the calibration and

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validation performance of those models using data collected on Dallas freeways, and provide recommendations for the use of the best model for congested freeways in Texas. The selected models were FREQ, INTEGRATION, and CORSIM.

After calibrating and validating the models with data obtained in Texas, they found that the models all performed relatively well for uncongested conditions; however, the performance became erratic and mostly unreliable for congested conditions. It appears that the models function better when allowed to begin simulation prior to the onset of congestion. Having data upstream and downstream of a freeway bottleneck or for a location of recurrent congestion helps the models to perform better.

It is apparent that people drive differently in congested versus uncongested conditions. None of the models tested allowed the user to dynamically change key model parameters (e.g., headway, lane changing, and driver behavior) to account for this driving difference. Besides that, the authors found that the proper and effective calibration of the models for a congested site requires that the users have good and extensive volume and travel time data, as well as origin and destination data. Simulating complex freeways layouts is always a complex task that requires skillful modelers and it is time consuming. Additionally, not all models can support such features.

The most important conclusion that the authors came up with was that the models they studied did not perform well at estimating recurrent congestion. Therefore, they would trust in engineering judgment over the simulation model output in most cases.

#### 2.3.1.3. Weather event impacts on traffic operations (Zhang, Holm, & Colyar, 2004)

This paper is the result of a project carried out for the Federal Highway Administration (FHWA). The objectives of this study were to identify how weather events impact traffic operations, and to assess the sensitivity of weather-related traffic parameters. To do so, they used the CORridor SIMulation (CORSIM) microscopic traffic simulation model, and developed guidelines for using the CORSIM model to account for the impacts of adverse weather conditions on traffic operations.

In their literature review, they looked for those factors that may have an effect on modeling traffic under adverse weather conditions. Based on that, they found a number of parameters, which they summarize in a Table. Although this table is big, it was decided to be included here (Table 2.3) to demonstrate the complexity and amount of variables that this approach involves, especially for weather conditions.

Table 2.3: Generic Traffic Simulation Parameters affected by adverse weather conditions (Zhang, Holm, & Colyar, 2004)

| Category                       | Parameters   |
|--------------------------------|--|
| Road geometry                  | <ul style="list-style-type: none"> <li>• Pavement condition (wet, dry, etc.)</li> <li>• Number of lanes</li> <li>• Lane width</li> <li>• Lane taper length</li> <li>• Segment link length</li> <li>• Shoulder type/width</li> <li>• Grade</li> <li>• Horizontal and vertical curvature</li> <li>• Super-elevation</li> </ul>   |
| Traffic control and management | <ul style="list-style-type: none"> <li>• Traffic signal</li> <li>• Ramp metering</li> <li>• Regulatory signs (Stop, Yield, Speed Limit, etc.)</li> <li>• Warning signs (Lane Ends, Merge Ahead, etc.)</li> <li>• Traveler information signs (Variable Message Signs, route guidance signs, etc.)</li> <li>• Surveillance detectors (type and location)</li> <li>• Lane use by movement (turn only, through only, shared through-turn)</li> <li>• Lane use by vehicle type (HOV, transit only, no trucks, etc.)</li> <li>• On-street parking</li> </ul> |
| Driver behavior                | <ul style="list-style-type: none"> <li>• Car following</li> <li>• Lane changing</li> <li>• Free-flow speed</li> <li>• Discharge headway</li> <li>• Startup lost time</li> <li>• Queue separation/spacing</li> <li>• Gap acceptance at intersections</li> <li>• Turning speed</li> <li>• Rubbernecking (response to incidents)</li> <li>• Illegal maneuvers</li> </ul>  |
| Events/scenarios               | <ul style="list-style-type: none"> <li>• Incidents/blockages (severity, duration)</li> <li>• Incident management (response, emergency vehicle dispatch, etc.)</li> <li>• Work zones</li> </ul>   |
| Vehicle performance            | <ul style="list-style-type: none"> <li>• Vehicle type distribution (% trucks, buses, etc.)</li> <li>• Acceleration/deceleration capability (stopping distance)</li> <li>• Turning radius</li> <li>• Vehicle length</li> </ul>  |
| Simulation run control         | <ul style="list-style-type: none"> <li>• Length of simulation run</li> <li>• Selected output MOEs (reports, animation files, etc.)</li> <li>• Resolution of simulation results (temporal and spatial resolution)</li> </ul>  |
| Traffic demand                 | <ul style="list-style-type: none"> <li>• Vehicle demand (including changes over time), expressed as Entry demands and turning percentages, and Origin-destination demands</li> <li>• Route choice</li> </ul>   |
| Multimodal operations          | <ul style="list-style-type: none"> <li>• Transit operations (routes, stops, headways, dwell times, etc.)</li> <li>• Bicycle operations (volumes, free-flow speeds, shared/exclusive paths, etc.)</li> <li>• Pedestrian operations (volumes, walking speeds, priority rules, sidewalk characteristics, etc.)</li> </ul>   |

Clearly, the authors analyzed this table and decided to shorten it, considering only the most relevant features within the list, which is not included here. These parameters were used in a sensitivity analysis to identify the most sensitive weather-related parameters in CORSIM. Each test parameter was modeled on various geometric networks and congestion (volume) levels using the default value and then changing

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the value to represent incrementally more conservative driver behavior, as would occur under adverse weather. Due to the large number of roadway networks, congestion levels, and parameters tested, approximately 45,000 individual CORSIM runs were completed. It has to be noticed that this is a large number of runs that implied lots of resources: time, hardware, and personnel, among others. In order to evaluate the results of these parameters studied, they developed a number of indicators (called Measures of Effectiveness MOE's), which are throughput (flow), vehicle-kilometers of travel, average speed, average density, and average delay. Based on them, they found that the parameters that have the largest sensitivity to weather are:

- Mean free-flow speed
- Car following sensitivity multiplier
- Time to react to sudden deceleration of lead vehicle
- Mean discharge headway
- Mean startup delay

After that, they presented the "Guidelines for Modeling Weather Events in CORSIM", which are the expected outcomes of the survey. This includes a seven-step process for developing a microsimulation model and how to apply the model to analyze various alternatives: Scope Project, Data Collection, Base Model Development, Error Checking, Model Calibration, Alternative Analysis, and Final Report. These guidelines have to be taken into account to develop models that forecast non-recurrent delays originated in adverse weather conditions. The mentioned parameters need to be evaluated in the application context (e.g. the Netherlands) in order to obtain truthful results.

#### 2.3.1.4. Queue discharge rate at incidents sites (Knoop, 2009)

This method is found in Chapter 4 in Knoop (2009). The main objective of this method was to determine the queue discharge rate at incidents sites. Therefore, this method concentrates on the supply side.

During incidents on motorways, clearly there is a decrease in capacity at the incident site as a result of less available lanes. Besides that, the author intended to prove that there is an extra capacity reduction due to the fact that remaining lanes are used less efficient because drivers are distracted. To do so, he categorized incidents in two groups. The first group is an incident situation where at least one of the lanes normally available for traffic (driving lane) is blocked. The other situation is where a car breaks down and stops at the shoulder lane of the motorway.

To determine the reduction of the queue discharge rate at incident locations it is required to have good estimates of the queue discharge rate during incident situations and in normal situations. During incident conditions, the queue discharge rate at the incident site, that is, the outflow out of the queue, can be derived from the counts at the downstream detector. Meanwhile, in normal conditions queue discharge rate is site-specific, like normal capacities. Apart from the

site-specific influences, there are likely to be behavioral influences. Besides that, the location of the incident in general is not a bottleneck for non-incident situations. Consequently, it is not possible to use the same method as during an incident to derive queue discharge rate. For this reason to find the queue discharge rate, the author decided to use a fit of a reverse-lambda shaped fundamental diagram, in which the intersection of the fit of the free flow branch and the congested branch is taken as queue discharge rate. This was done using data collected for the periods of 10 days before and 10 days after the incident.

In order to compare regular situations against the incident situations, the author came up with two indicators. First, he considered that under normal conditions the queue discharge rate is  $C_{non-incident}$ , and during an incident this is reduced to  $C_{incident}$ . The quotient of the two queue discharge rates is the fraction of the capacity that remains,  $F$ . The reduction of the queue discharge rate is a combined effect of the reduction of the number of lanes  $n$  and the less efficient use of the remaining lanes. Expressing the efficiency  $\eta$  of the use of the remaining lanes by dividing the capacity factor by the fraction of the roadway that is available, gives:

.....  
Equation 2.5

$$\eta = \frac{F}{\frac{n_{incident}}{n_{non-incident}}} = \frac{C_{incident}}{\frac{n_{incident}}{n_{non-incident}} C_{non-incident}}$$

For feeding the model (calibration), the author selected incident data from the A1, A2, and A4 motorways in the Netherlands in the period comprised between January 1<sup>st</sup> and July 31<sup>st</sup> in 2007. The resulting capacity factor  $F$  and efficiencies of the use of the remaining lanes  $\eta$  are presented in Table 2.4. As it may be noticed, the variable capacity factors (for the Netherlands) listed in the table above, were also reported for the United States by TRB (2000), and showed in Table 2.1. Comparing values in these tables is possible to perceive that the capacity factors in the United States are somewhat higher than in the Netherlands, except for two lanes blocked, which are almost the same.

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Table 2.4: Resulting capacity factors and efficiency of lane use (Knoop, 2009).

| Type of blocking              | Shoulder | 1 out of 3 | 2 out of 3 | Rubbernecking |
|-------------------------------|----------|------------|------------|---------------|
| Mean                          | 0.72     | 0.36       | 0.18       | 0.69          |
| Standard deviation            | 0.09     | 0.14       | 0.12       | 0.08          |
| Efficiency of lane use $\eta$ | 0.72     | 0.54       | 0.54       | 0.69          |

The developed method was used in a case of incident management, although it cannot be said that this was the validation of it. To determine the delay, the demand for a non-incident day and the capacities during the incident were put into a traffic simulator. This equals a situation where people would not change their route because of the incident. The simulator predicted the queue length and delay if the outflow was blocked for a while by the incident.

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The most important finding is that the capacity per lane reduces significantly due to a change in driving behavior. The size of this reduction depends on the incident type. If one of the driving lanes is blocked, the remaining lanes are used 46% less efficient, which yields an “efficiency factor” of 54%. If there is an incident at the shoulder lane, the efficiency reduces by 28%. This is only due to a change in driving behavior since all the lanes are open. A similar efficiency drop (31%) is found in case there is an incident at the other side of the guardrail, resulting from the “rubbernecking” effect. As it was observed, this method was applied for an incident management case, which one of its main objectives is to reduce delays originated in incidents (non-recurrent cause of congestion).

#### 2.3.1.5. Simulation-based approaches Conclusions

As was presented in Figure 2.4, simulation-based approaches use traffic simulation models that are fed on the one hand by network layout (configuration) and features (parameters) and on the other hand by real data. This structure was present in all of the methods studied.

In the studies reviewed, modeling the networks traffic flows without congestion had minor problems; the main issue was to model the congested situation. This could be due to the fact mentioned in Knoop (2009): besides the physical capacity reduction caused by blocking events, there are additional effects due to changes in driving behavior. This dynamic driving behavior is not easy to include and often not included in the models at all.

As it might be noticed, simulation-based approaches are mainly used for simulating traffic flow for a time period from the prediction time onwards. It means that they are mainly used to forecast traffic conditions (online), which results are essential in ITS applications. However, this is not the same case in this study, where the main objective is to assess the delays produced by certain non-recurrent events, rather than predict it. Therefore, this strength is not totally useful for this study.

Building the traffic model is a complex task, since it is necessary to digitalize the network with its features (layout, traffic demand, etc). Although any model is a simplification of the reality, the model needs at least to resemble it. Thus, this is a time consuming task that requires skilful people and it needs to be kept up-to-date with all disturbing occurrences (e.g. roadworks). Besides that, it also needs specialized software which is expensive.

In order to get the model work properly (be as close as possible to reality) it needs to determine (calibrate/validate) a number of parameters. Some of them are quite hard to determine and require many default parameters, especially those related with highly stochastic behavior such as driving behavior. Furthermore, they are difficult to observe/measure and it tends to be expensive to obtain and maintain. In the case of non-recurrent events, perhaps the most complex model

involving lots of parameters are the adverse weather conditions, as was presented above. The table with the parameters affected by it and therefore needed to be measured, was presented both in regular and in adverse weather conditions. In this case (Zhang et al., 2004) the task demanded a team of experts working for more than one year.

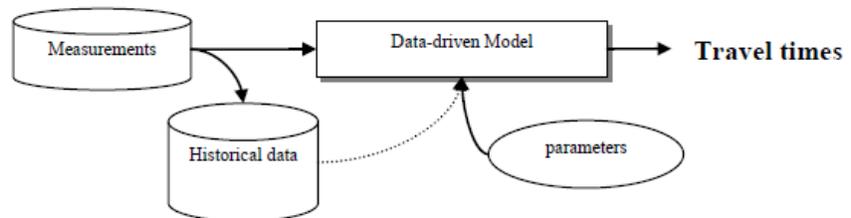
In any case, modeling involves to make (lots of) assumptions/simplifications in their attempt to reproduce reality. As one might expect, these assumptions may lead to bias in the results. It is also the case that the less information (parameters) available, the higher the uncertainties. It also brings about that the user must look at the model outcomes critically.

Following the sequence established at the beginning of this section, the next segment includes a review of the second category of methods to calculate non-recurrent delays.

### 2.3.2 Data driven approaches

Data driven models use general mathematical models such as multivariate regression, ARIMA, and neural networks to regress the expected traffic characteristics over a route from historical (and current) traffic data. The general structure of this approach is presented in Figure 2.6 (van Lint, 2009).

Figure 2.6: Schematic outline of simulation-based traffic models (van Lint, 2009).



In the figure above it can be seen that the structure of these approaches start from measurements that are stored in databases (historical data) and they also need some parameters. Again, the model outcome is the estimation of the traffic conditions in the network, and the variable of interest was travel times, which is not the case in this study, where the variables of interest are congestion and delays.

Once more, there are a lot of data driven models to estimate traffic conditions, but this section will focus on those models that are related with non-recurrent congestion. In the following, these methods are described, with their main objectives and results.

#### 2.3.2.1. Delay caused by incidents, special events, lane closures, and adverse weather (Kwon et al., 2006)

The presented method divides the total congestion delay ( $D_{total}$ ) on a freeway section into six components: the delay caused by incidents ( $D_{col}$ ), special events ( $D_{event}$ ), lane closures ( $D_{lane}$ ), and adverse weather ( $D_{weather}$ ); the potential reduction in delay at bottlenecks that ideal ramp

metering can achieve ( $D_{pot}$ ); and the remaining delay ( $D_{excess}$ ), caused mainly by excess demand. The method involves two steps. First, the components of non-recurrent congestion are estimated by statistical regression. Second, the method locates all bottlenecks and estimates the potential reduction in delay that ideal ramp metering can achieve.

The method applies to a contiguous section of motorway with  $n$  detectors indexed  $i = 1, \dots, n$ , each providing flow (volume) and speed measurements averaged over 5-minute intervals indexed  $t = 1, \dots, T$ . The days in the study period are denoted by  $d = 1, 2, \dots, N$ . The  $n$  detectors divide the motorway section into  $n$  segments. Each segment's (congestion) delay  $d_i(t)$  is defined as the additional vehicle-hours traveled driving below free flow speed  $v_{ref}$ , taken to be 60 mph (96.5 km/h). Thus, the delay  $D_i$  (in vehicle hours) in segment  $i$  in time  $t$  is:

Equation 2.6

$$D_i = l_i * q_i(d, t) * \max\left(\frac{1}{v_i} - \frac{1}{v_{ref}}, 0\right)$$

Where  $l_i$  is the segment length,  $q_i$  is the vehicle volume and  $v_i$  is the speed. The total daily delay  $D_{tot}$  in the motorway section is the delay over all segments and times:

Equation 2.7

$$D_{total}(d) = \sum_{i=1}^n \sum_{t=1}^T D_i(d, t)$$

As it was mentioned, the components of the delay are obtained using statistical regression with the following model:

Equation 2.8

$$D_{total}(d) = \beta_0 + \beta_{inc} X_{inc}(d) + \beta_{roadw} X_{roadw}(d) + \beta_{weather} X_{weather}(d) + \epsilon(d)$$

Where:

|                    |   |
|--------------------|---|
| $\epsilon(d)$ :    | Error term with mean zero                             |
| $X_{inc}(d)$ :     | Number of incidents on day $d$                        |
| $X_{roadw}(d)$ :   | Number of roadworks on day $d$                        |
| $X_{weather}(d)$ : | 0-1 indicator of adverse weather condition on day $d$ |
| $\beta_j$ :        | Parameter estimates                                   |

Fitting the model to the data via linear least squares gives the parameter estimates, denoted  $\beta_0$ ,  $\beta_{inc}$ ,  $\beta_{roadw}$ , and  $\beta_{weather}$ . The intercept  $\beta_0$  is the delay when there are no incidents, roadworks, or adverse weather conditions. Thus, consistent with convention, it may be identified with recurrent congestion  $D_{rec}$  since it equals total delay minus the non-recurrent delay  $D_{non-rec}$ :

$$\beta_0 = D_{rec} = D_{total} - D_{non-rec}$$

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## Results

The method has been applied to a 45.33 mi (72.9 km) section of southbound (SB) and northbound (NB) I-880 in the San Francisco Bay Area. Two periods are considered: morning peak (AM), 5:00 to 10:00 a.m., and evening peak (PM), 3:00 to 8:00 p.m. Data cover 110 weekdays from January 5 to June 30, 2004. Therefore, there are four datasets, distinguished by peak period and freeway direction: SB AM, SB PM, NB AM, and NB PM.

The first analysis performed was the statistical significance of the coefficients  $\beta$ . With those statistical significant variables they conclude that:

- Aggregating over both peaks and both directions, the delay components are 13.3%, 4.5%, 1.6%, 33.2%, and 47.4% for incidents, special events, rain, potential reduction, and excess demand, respectively. Notice that almost one-half of the delay is caused by excess demand in both directions.
- The vehicle hours of delay per incident are 486.13 (NB) and 383.75 (SB) for the evening shift.
- The average daily delay caused by incidents  $D_{inc}$ , is 986 and 837 vehicle hours for NB and SB, respectively.

As it may be seen, this is a relatively easy to use method to determine the congestion and its components. It is also easy to add new variables to the regression. For these reasons, it is considered valuable. In spite of this, it is also a quite straightforward, complete statistical method, which misses to interpret the causal relationships of the variables. Therefore, this kind of analysis is basically a statistical tool checking the coefficients rather than understanding the traffic flow phenomena.

### 2.3.2.2. Delay caused by collisions (Kwon & Varaiya, 2005)

The considered causes of non-recurrent congestion in this method were collisions, potential ramp metering gain, and excess demand. The last cause does include not only the excess demand, but also all other causes including non-collision incidents, lane closures, and weather. So, at the end the only cause of non-recurrent congestion explicitly obtained in this method is collisions.

The definition of delay (including sub-dividing the road in sections, et cetera) is the same as in the previous case (Equation 2.6 and Equation 2.7). Formally, the method divides the total delay  $D_{tot}$  (calculated from flow and speed data) into three components:

$$D_{tot} = D_{col} + D_{pot} + D_{rem}$$

With:

$$D_{rec} = D_{tot} - D_{col}$$

Where:  $D_{col}$ : Total daily delay caused by collisions  
 $D_{rec}$ : Daily 'recurrent' delay

---

$D_{pot}$ : Potential reduction of  $D_{rec}$  by ramp metering  
 $D_{rem}$ : Residual delay attributed mostly to excess demand

The paper shows the method to determine delay from collisions  $D_{col}$ . The authors declare a freeway segment  $i$  to be congested during a 5-minute time  $t$  if the speed  $v_i(t) < 50$  mph (about 80 km/h). However, in the delay calculation the authors took the free flow speed of 60 mph. Using this definition of a congested state, the incident impact algorithm determines the duration-extent 'rectangle' of a collision's impact. To obtain the delay contribution of the collision, it must be subtracted from the total delay the recurrent delay (that would have occurred in the absence of the collision), in the way in which is presented later on.

For each collision  $a$ , the algorithm first finds the nearest segment  $i_a$  upstream of the (known) collision location  $s_a$ . Then, it checks whether the speed in segment  $i_a$  is below 50 mph at any time within 15 minutes after  $t_a$ . If there is such a speed drop, the algorithm searches for the longest consecutive time block ( $t_a + 15$  min, ...,  $t_a + A_a$ ) throughout which the speed at  $i_a$  is below 50 mph. This longest time block is the collision duration of  $a$ . For each time  $t \in (t_a, \dots, t_a + A_a)$ , search upstream until the speed recovers to above 50 mph to obtain the set of congested segments. The extent of collision  $a$  is the largest set of segments  $B_a$  among the  $B_a(t)$ , that have a speed lower than 50 mph:

.....  
Equation 2.9

$$B_a(t) = \{ j < i_a : v_k(t) < 50 \text{ mph, for all } k \text{ with } j \leq k \leq i_a \}$$

.....  
Equation 2.10

$$B_a = \bigcup_{t=t_a}^{t_a+A_a} B_a(t)$$

Repeating this procedure for all collisions gives the duration-extent rectangle  $(A_a, B_a)$ , for each collision  $a = 1, 2, \dots$ .

The recurrent congestion  $D_{rec}$  is estimated as the K-nearest neighbor prediction of the recurrent delay, based on historical data of the delay  $D_a(t, d)$  during the same time  $t$  and over the same spatial extent, for several other days  $d = 1, \dots, D$ . The estimate of the recurrent congestion is the median value:

$$D_{rec}(t) = \text{median} \{ D_a(t, d_k), k = 1, \dots, K \}$$

In which  $d_k, k = 1, \dots, K$  are  $K$  days with smallest value  $|D_a(ta, d) - D_{tot,a}(t_a)|$  for  $d = 1, \dots, D$ . The recurrent congestion over the duration-extent of collision  $a$  is estimated to be:

.....  
Equation 2.11

$$D_{rec,a} = \sum_{t=t_a}^{t_a+A_a} D_{rec,a}(t)$$

---

Based on this, it is possible to obtain  $D_{col}$ , subtracting the previous value from the total delay. Afterwards, the algorithm describes the potential delay reduction by ramp metering  $D_{pot}$ , which is considered not relevant in this case and therefore is omitted.

### Results

The method was applied in a case study, which was a 22.5 mile section of northbound I-15 in San Diego County. The time period is from 5 AM to 8 PM, for 44 weekdays (September 2-October 31, 2002). There are 24 loop detectors in the section for which 5-minute lane-aggregated volume and speed data are obtained. There were 74 collisions during the study period, and the calculated average daily delay was 5,672 vehicle-hours.

On average, each collision induces a delay of 477 vehicle-hours. Only 25 of 74 accidents (33%) cause any delay and nearly 70% of collisions cause no delay. The distribution illustrates the '10-90 rule': 10 percent of collisions account for 90 percent of collision-induced delay. The average daily delay caused by collisions,  $D_{col}$ , is 802 vehicle-hours, which is 12.4% of total daily delay. The authors found that in the afternoon, when there is high recurrent congestion, there is a greater chance of collision and greater delay than in the morning, especially if the collision occurs at the beginning of the recurrent congestion period. The average impact of collision on congestion is most severe when the freeway is moderately congested with high volume.

This method has interesting aspects, such as the algorithm to determine the extension of congestion in time and space. Additionally, the causality between collisions and delays are explicit, in contrast to the prior method. The drawbacks are the way to estimate the recurrent delays, correlating historical data of the days with the closest delays. As it was noticed, they did not mention how many days should be included or which days may be considered as representative to make the correlation. The other disadvantage is that the algorithms only consider explicitly collisions, and the rest of the causes of congestion (both recurrent and non-recurrent) are not distinguished.

#### 2.3.2.3. Delay caused by lane blocking events, construction lane closures, and inclement weather (Hallenbeck et al., 2003)

As mentioned before, the causes of congestion considered in this survey were lane blocking accidents and disabled vehicles, other lane blocking events (e.g., debris in the roadway), construction lane closures, and inclement weather. The steps of the algorithm applied are summarized in the following:

- Determine vehicle volume, speed, and lane occupancy by time and location.
- Identify the days affected by lane blocking incidents.
- For all days when lane-blocking incidents did not occur, compute the median condition by time of day and location. This median condition serves as the "expected, recurring, condition"  $C_{rec}$ .

- 
- For each day, compute the times and locations where congestion was “significantly worse”  $S_w$  than  $C_{rec}$ . That is a change in lane occupancy greater than 5 %. These locations are sites of “non-recurring congestion”.
  - For all days when major lane blocking incidents took place, determine the time, location, and duration of each incident recorded.
  - For all days when major lane blocking incidents took place, determine the geographic and temporal extent of  $S_w$ .
  - Using the 60 mph baseline standard, compute the delay associated with each of  $S_w$  geographic and temporal areas associated with lane blocking incidents. These are the estimates of non-recurring delay caused by lane blocking incidents.
  - Using the 60 mph baseline speed, compute the delay associated with all areas where and times when conditions are defined as  $S_w$  for all days. This includes the delay associated with incidents, as well as all other non-recurring delay. This is the estimate of total non-recurring delay.
  - For all days compute the total delay, which is any travel slower than free flow conditions (60 mph).
  - Subtract from the estimate of total delay the non-recurring delay computed above. The result is the total recurring delay based on a 60 mph standard.
  - Repeat the preceding four steps, with a 50 mph baseline speed.
  - Aggregate and summarize these levels of delay across corridors and for different time of day/volume conditions within corridors.

In this paper the authors chose two possible scenarios to calculate the temporal and spatial extension of  $S_w$ . One provided a conservative estimate of “incident related congestion,” meaning that much of the congestion occurring in the vicinity of the incident after it had been cleared was attributed to background traffic volumes and was not associated with the incident. The second approach, the “liberal estimation”, assigned the majority of congestion contiguous to the location of the incident and after its occurrence to that incident.

### Results

In the case study, the selected research approach restricted the analysis of recurring and non-recurring congestion to weekdays, and specifically, Tuesday through Thursday. In addition, the analysis was broken into four specific time periods: AM peak (6:00 to 9:00 AM), midday (9:00 AM to 3:00 PM), PM peak (3:00 to 7:00 PM), and night. Geographically, the study included the mainlines of the entire central Puget Sound metropolitan freeway system in the Washington State, in the United States. That includes five separate, connected freeways and roughly 100 center-line miles of roadway. Data for two months were used, covering September and October of 2002.

The results obtained for all of the freeways in the survey area are presented in tables, and the values are scattered. For instance, for a reference speed of 50 mph, the total delays obtained (in the whole

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period analyzed) varied from 19.000 to 161.000 veh.h. The percentage of delay caused by lane blocking incidents (liberal estimate) went from 2.0% to 23.3%. In the same way, the percentage of the non-recurring delay of the total delay ranges from 19.5% to 77.5%. The freeways with the highest and lowest values of total delay are not the same as those with highest and lowest percentages of non-recurrent delay or delay caused by blocking incidents.

Furthermore, the authors came up with a unitary indicator, the delay per lane-mile, which range from 1.500 to 7.500 veh.h. Once again, the road stretches with the extreme values are different from that described above.

In the report only the results are presented and they are not further elaborated, nor are the differences explained. Consequently, the reasons for those variations are not clear and they may be attributable to the stochasticity of the traffic operations.

This report presents an algorithm with advantages like being both good structured and relatively simple to obtain non-recurrent delays caused by lane blocking incidents. It has some disadvantages as it determines the non-recurrent congestion due to lane blocking incidents and the total non-recurring congestion independently, which may result confusing. It is also makes the report unclear the scenarios proposed (liberal and conservative). This can be improved applying the procedure for determining the spatial and temporal extension of the delay, shown in the previous paper. The threshold to determine the base condition  $C_{rec}$  can be further elaborated. It did not explain the consequences of lane blockings such as changes in routes (network effects), described above.

#### 2.3.2.4. Online measuring of delay caused by accidents (Recker et al., 2005)

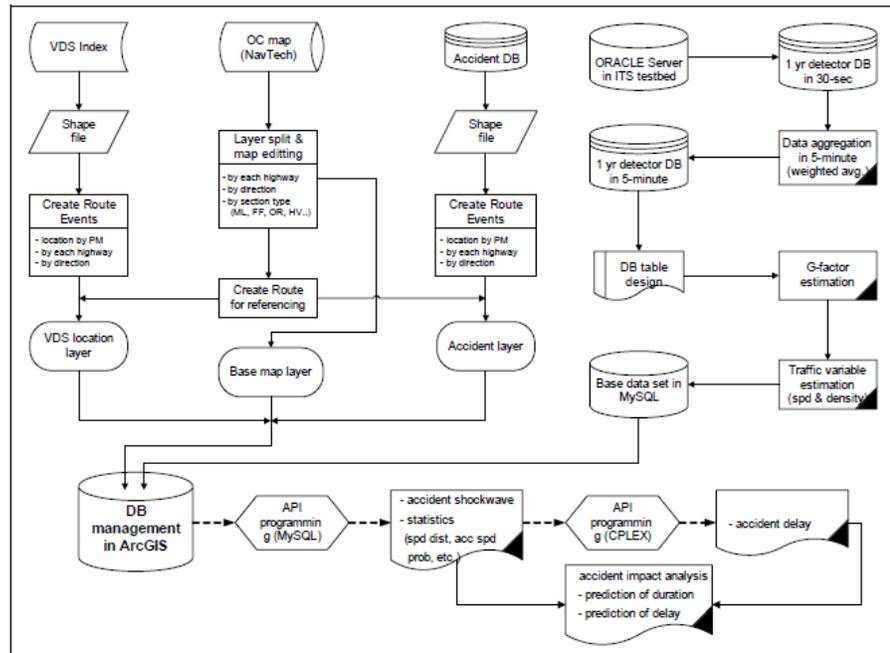
The main objective of this research project is to develop and apply an analytic procedure that estimates the amount of traffic congestion (vehicle hours of delay) and the temporal and spatial extent of accident-related congestion in real time, caused by different types of accidents that occur on urban freeways in California. This 'real time' characteristic implies handling large amounts of information in databases, and therefore this database management is included in the method. This feature differs from the objectives and the scope of this study.

The overall process may be seen in Figure 2.7. The procedure uses a G-factor, because loop detectors in Orange County are single loop detectors that provide only traffic counts and occupancies; thus, the travel speeds need to be estimated from these measures. Then the "g-factor" is the summation of the average vehicle length and effective detection length. This method depends greatly on this value.

## Results

The method to compute non-recurrent delay was performed for 870 accidents that occurred on weekdays throughout the period of March through December 2001 on the six major Orange County<sup>2</sup> freeways. The number of breakdowns by freeway is: I-5 (222 accidents), I-405 (157 accidents), SR-22 (153 accidents), SR-55 (94 accidents), SR-57 (138 accidents), and SR-91 (106 accidents).

Figure 2.7: Overall process online measuring of delay caused by accidents (Recker et al., 2005)



The median total delay for these 870 accidents is 86 vehicle hours, the lower bound of the mean is 184 vehicle hours, and the lower bound of the standard deviation is 246. As indicated by the difference between the median and the high standard deviation relative to the mean, the distribution of non-recurrent delay is highly skewed to the right (i.e. toward high values of delay).

In the survey, the authors found that accidents occurring during the weekday afternoon peak hours (3:30 through 6:30 PM) lead to the most delay (225 veh.h), followed by mid-day accidents (9:01 AM through 3:29 PM). As expected, accidents either after 6:30 PM or before 6 AM result in the least delay. Similarly, the authors computed average delays per day of the week showed that the worst day is Friday (240 veh.h), followed by Tuesday, Thursday and Wednesday. Accidents that occur on Monday contribute the least to total non-recurrent delay.

<sup>2</sup> California, United States

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As it was mentioned before, this method aims to forecast the delays on-line, thus most of these developments cannot be used in this survey. However, this is a complete method that includes huge amounts of data, which may make it robust. In case the findings of this thesis would be extended to estimate non-recurrent delays on-line, it would be interesting to include the developments made in this paper.

#### 2.3.2.5. Conclusions on Data driven approaches

In the data driven approaches studied it could be observed that the methods vary in a range of complexity and data required. For instance, within the cases studied only the method developed by Recker et al. (2005) was designed to work online and therefore it requires handling large databases online, which is not the case for the rest. It also makes it somehow complex to implement especially considering that it requires more resources (e.g. software, hardware, etc.).

In contrast, the method that was considered the simplest to apply was Kwon et al. (2006), as it includes mainly linear regression of the variables considered. However, this is considered a statistical tool checking coefficients rather than understanding the traffic flow phenomena, correlating delays with its causes. This method, as well as Kwon & Varaiya (2005), has the delay definition (Equation 2.6 and Equation 2.7) that is used in all the papers studied. This definition will be also employed in this study.

As it was expected based on the information presented on Figure 2.6, all the examined methods require databases with historical flows and speeds and data on the non-recurrent occurrences analyzed. This information is also required in this study.

All the methods studied have approximately the same structure: first they compute non-recurrent delays, then they determine total delays and finally the recurrent delays are obtained as the difference between them. Since recurrent delays are those that are present most of the time, they could be both estimated more accurately and better characterized. For that reason, it is considered that this feature may be improved, and the recurrent delays should be calculated first, and base on it, determine non-recurrent delays.

One of the drawbacks of most of the analyzed methodologies was that they tackle only one cause of non-recurrent delays (e.g. collisions, incidents, accidents, blocking lanes). They group the unconsidered causes in other categories, but they do not explicitly cope with them. Only Kwon et al. (2006) include several causes of non-recurrent delays, with the additional advantage that any other unconsidered cause in the paper could be easily added. Obviously, these advantages are required to be included in the methodology that will be proposed in this study, compensating for the negative aspects of this method.

Taking a look at the outcomes of the different papers reviewed, Table 2.5 was built with the intention of summarize values reported on the

literature. In this way it is easier to compare the results from different sources. In this table there is an odd low value for delay, reported in Recker et al. (2005). This is the average delay per accident of 86 veh.h, which could be the result of including the delay of all of the incidents in the period studied, and this study has data for 24 hours per day. Naturally, there are periods of the day that the accidents do not bring about many delays e.g. in the nights.

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**Table 2.5: Summary of the results of the data driven models reviewed**

| No. | Method                   | Quantity (Average)        | Value              |
|-----|--------------------------|---------------------------|--------------------|
| 1.  | Kwon et al. (2006)       | Delay per incident        | 384 to 486 veh.h   |
|     |                          | Daily delay of incidents  | 837 to 986 veh.h   |
|     |                          | % Non-recurrent delay     | 19.4%              |
| 2.  | Kwon & Varaiya (2005)    | Delay per collision       | 477 veh.h          |
|     |                          | Daily delay of collisions | 802 veh.h          |
|     |                          | % Non-recurrent delay     | 12.4%              |
| 3.  | Hallenbeck et al. (2003) | Delay per lane-mile       | 1500 to 7500 veh.h |
|     |                          | % Delay lane blockings    | 2 to 23%           |
|     |                          | % Non-recurrent delay     | 20 to 78%          |
| 4.  | Recker et al. (2005)     | Delay per accident        | 86 veh.h           |
|     |                          | Delay afternoon peak      | 225 veh.h          |
|     |                          | Delay on Friday           | 240 veh.h          |

As it was expected, authors express their results in their own terms, which are not necessary the same as the others. The important point is to see the order of magnitude of the delays, to facilitate the comparison with results obtained in this study.

### 2.3.3 Approach evaluation and selection

After studying literature on these two different approaches that deal with estimation of non-recurrent delays, it is necessary to select one approach, which will be used in this study. This selection is made using a Multi-Criteria Decision Analysis. Since hard data are not available about the available alternatives, and the scores and weights are qualitative, the most suitable method (among the diverse in MCDA methods) is qualitative outranking (van Ham, 2008). This method compares the performance of multiple alternatives on the selected criteria according to the qualitative scores.

The first step in this method is to identify the available options. In this case, it is clear that the options are the simulation-based approach (A1) and data driven approach (A2). The next step is to define the criteria to evaluate the alternatives, which match with the objectives of this study, mentioned in the first chapter. Along the review made to the different methods to assess non-recurrent congestion, in both simulation-based and data driven approaches, it was noticed that there are significant subjects that condition the performance of the models. Naturally, these factors are picked to be the selection criteria used in the MCDA, and they are listed below:

1. Assumptions made (C1): Amount of assumptions that are necessary to make, in order to achieve the model to work (the less the better).

2. Easiness to develop the model (C2): How undemanding is to develop and use the model.
3. Parameters required (C3): It is related to number of parameters involved in the model (as was mentioned before).
4. Time to obtain results (C4): How fast the model can obtain results.
5. Explicit correlation between occurrences and congestion (causality) (C5): how clear is to identify the causes of congestion and to correlate them with the delays obtained.
6. Network impacts (C6): Easiness to include the behavior of traffic of the network.
7. Flexibility (C7): Easiness to include different factors such as several causes of non-recurrent congestion.
8. Representativeness and validity (C8): How good the model results characterize the 'real world'.
9. Assessing mitigating actions (C9): How simple is to assess the impacts of diverse measures to mitigate non-recurrent congestion.

Initially it was considered another criterion: the amount of data required to feed the model. However, taking into consideration that both approaches perform very close in this criterion, it was left out because it does not contribute in the selection.

Subsequently, alternatives have to be ranked, according to their performance in the criteria defined: the alternative that performs best in a criterion obtains the first rank (1), while the other has the second place (2). All the criteria and their ranking are shown in Table 2.6. The next step in the method is to give a qualitative weight to each of the criterion to reflect their importance in the decision, which is in the last column of Table 2.6. It was considered that the most important criteria were easiness to develop the model and explicit correlation between occurrences and congestion, and hence they have the highest weight.

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**Table 2.6: Multi-Criteria Decision Analysis MCDA qualitative outranking**

| Criteria  | Alternatives                  |                          | Weight |
|---|-------------------------------|--------------------------|--------|
|   | A1: simulation-based approach | A2: data driven approach |        |
| Assumptions made  | 2                             | 1                        | 10%    |
| Easiness to develop the model                           | 2                             | 1                        | 15%    |
| Parameters required                                     | 2                             | 1                        | 10%    |
| Time to obtain results                                  | 2                             | 1                        | 10%    |
| Explicit correlation between occurrences and congestion | 1                             | 2                        | 15%    |
| Network impacts   | 1                             | 2                        | 10%    |
| Flexibility   | 1                             | 2                        | 10%    |
| Representativeness and validity                         | 2                             | 1                        | 10%    |
| Assessing mitigating actions                            | 2                             | 1                        | 10%    |

The next step in the MCDA qualitative outranking is to transform the rankings in scores as: minus one (-1) when the alternative is in the second place and plus one (+1) when the alternative is in the first place. The weighted sum of the alternatives, to compare them is:

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$$M_{A1A2} = (-1 \times 0.10) + (-1 \times 0.15) + (-1 \times 0.10) + (-1 \times 0.10) + (+1 \times 0.15) + (+1 \times 0.10) + (+1 \times 0.10) + (-1 \times 0.10) + (-1 \times 0.10) = -0.3 \rightarrow A1 < A2$$

$$M_{A2A1} = (+1 \times 0.10) + (+1 \times 0.15) + (+1 \times 0.10) + (+1 \times 0.10) + (-1 \times 0.15) + (-1 \times 0.10) + (-1 \times 0.10) + (+1 \times 0.10) + (+1 \times 0.10) = 0.3 \rightarrow A2 > A1$$

Thus, the performance of alternative 2 (data driven approaches) is has a better performance than alternative 1 (simulation based approaches) in the selected.

After obtaining these results, a sensitivity analysis was carried out (not included here) which showed that even when changing the weight assigned to each criterion, still Alternative 2 (data driven approaches) has a better performance. This may arise in the fact that the strongest points of the simulation-based approaches are to obtain results online and forecast traffic state, which is not the case here.

Among the data driven methods studied to calculate non-recurrent delays, it is proposed to create a new structured method that combines the main advantages of the presented methods. One of the general criterion selected to choose an alternative was to take explicitly into account the causal relation between (non-recurrent) occurrences and delays. This is considered quite important to clearly understand the causes that trigger congestion. It leads to leave out the method developed by Kwon et al. (2006), since it lacks of this explicit relation. Yet, it has strong points such as consider various (more than one) causes of congestion and the possibility to easily include more causes of non-recurrent congestion (not included in the original study). Those points will be contemplated. From the Kwon & Varaiya (2005) method it is important to take the delay definition and extension of congestion (Equation 2.6, Equation 2.7, and Equation 2.9). Finally, from the Hallenbeck et al. (2003) method will be taken its structured approach. This method will be developed later on, in Chapter 4.

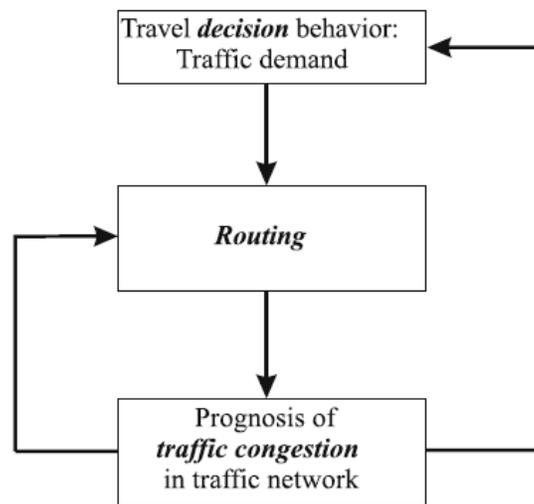
## 2.4 Network Effects

In the 'real world', the traffic system operates in networks rather than on isolated road stretches. These networks show complex behavior underlain by complex relationships between already identified traffic characteristics. These complexities influence choices like departure time and route (both pre-trip and on-trip), among others. In this way, the traffic flows on the network are affected. For this reason, it is necessary to have insight into the network dynamics and spillback and downstream effects, in order to evaluate the effects of the non-recurrent congestion in the network.

Traffic congestion propagates within a traffic network through spatiotemporal congested traffic patterns, which exhibit a variety of complex features. The complexity of vehicular traffic is due to nonlinear interactions between the following three main dynamic processes, as illustrated in Figure 2.8 (Kerner, 2009).

- Travel decision behavior, which determines traffic demand.
- Routing of vehicles in a traffic network.
- Traffic congestion occurrence within the network.

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**Figure 2.8: Explanation of complexity of vehicular traffic (Kerner, 2009).**



These processes interact, since travel decision behavior determines travel demand. Traffic routing in the network is associated with traffic supply at specific locations and time periods. However, traffic congestion occurring within the traffic network restricts free flow travel. This influences both travel decision behavior and traffic routing in the network (both pre-trip and en-route), although this is not clear in Figure 2.8, as it only is mentioned ‘routing’. The influence could be seen for instance when a person decides to stay at home or travel by train rather than by car, because of road traffic congestion. As a result, there is a feedback between traffic congestion and travel decision. In turn, because of traffic congestion on a route usually used, a person may change travel route (Kerner, 2009).

Figure 2.8 shows a causal relationship between travel decision, routing and congestion on the road network. The occurrences on the network have impact on the first two elements and thus travel decision and routing affect congestion on the network.

Knoop (2009) states that a queue (and delays) on a particular stretch of road will lead to an increase in travel time on a route which incorporates that stretch, making it less attractive to travelers. This queue (increase in travel time) may stimulate travelers to take another route, which reduces the inflow in the original route. Consequently, queues decrease (or grow slower) compared to an unchanged demand. Therefore, queues and delays lead to changes in route choice behavior and route demand.

It was mentioned above that non-recurrent causes of congestion often create bottlenecks and consequently queues and delays occur, influencing some drivers’ choices (such as route, departure time, and

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destination). This may generate traffic diversion, increasing the inflows in other links, which are not regular or expected. This was referred to as 'network effects' in section 2.2. Hence, it is required to study the potential effects that non-recurrent causes of congestion have on the traffic on the network.

To describe traffic in a network, traffic flow theory is necessary although not sufficient, since these theories do not fully predict how traffic is distributed over the network. Therefore, it is necessary to make use of other techniques. Basically, there are three methods of quantitatively describing network traffic flow, which imply making different assumptions, require different inputs, and produce different outputs. Those methods are split fractions at nodes, disaggregated turn fractions per destination, and identify all possible/feasible paths (=routes) for each OD pair (van Lint, 2009). Considering the data available and the objectives of this study, it was concluded that the first method (turn fractions at nodes) will be used.

The 'split fractions at nodes' method considers the percentage of the total flow arriving at a node from one direction, going left or right or through. In this case, one does not consider route choice and for inputs only total inflows at the origins are needed (van Lint, 2009). The theoretical background behind this method is explained in the following. It has to be taken into account that the approach selected for the survey is to take real (empirical) data, hence looking at the theoretical background lets us to compare both results and to derive some conclusions.

This theoretical background about split fractions at nodes could be found in Knoop (2009). He used the shockwave theory to explain the behavior of the flows (split fractions) and delays associated with them in an intersection, when an incident occurs in its vicinity. His main objective was to correlate the duration of the incident and the total delay caused over the drivers. To do so, he used shockwave theory including network characteristics, in order to obtain formulae that correlate these two variables (incident duration and total delay). These formulae also included the capacity reduction factor ( $r$ ) due to the incident (which depends on the number of lanes blocked and changes on driving behavior), and the split fraction  $\psi$ , among other variables. This is considered significant in this thesis as he explained the dynamics of the split fractions under road blockages, although his main objective differs slightly from those mentioned here.

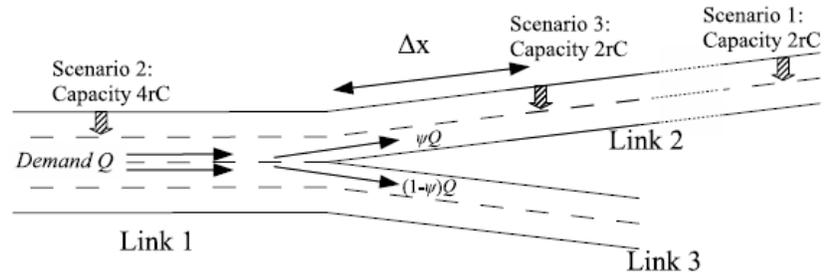
The incidents considered are in the vicinity of a junction, either downstream or upstream. It is clear that these incidents have impacts on the dynamics of the network, which could affect the split fractions on the links. The general layout used by Knoop (2009) is presented in Figure 2.9<sup>3</sup>, where the locations of the incidents can be seen with respect to the intersection (upstream or downstream). The link under

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<sup>3</sup> These are the basic configurations and more cases could be derived from them

study is Link 2 and the principal link is Link 1, which handles the total demand  $Q$ . It is clear that the total demand  $Q$  is split into Links 2 and 3, with the main split fraction  $\psi$  going to Link 2 (therefore assumed as higher than 50%) and the remaining  $(1-\psi)$  going to Link 3, in normal conditions.

Figure 2.9: Road layouts studied with the incident location (Knoop, 2009)



The dynamics and split fractions at the nodes for the different scenarios presented in Figure 2.9, are summarized in the tables and figures below, as indicated:

- Scenario 1 (No influence of Junctions): Figure 2.10 and Table 2.7.
- Scenario 2 (Incident upstream of a junction): Figure 2.11 and Table 2.8.
- Scenario 3 (Queues longer than the distance to the junction): Figure 2.12 and Table 2.9.

Figure 2.10: Traffic states for a temporal bottleneck, Scenario 1 (Knoop, 2009)

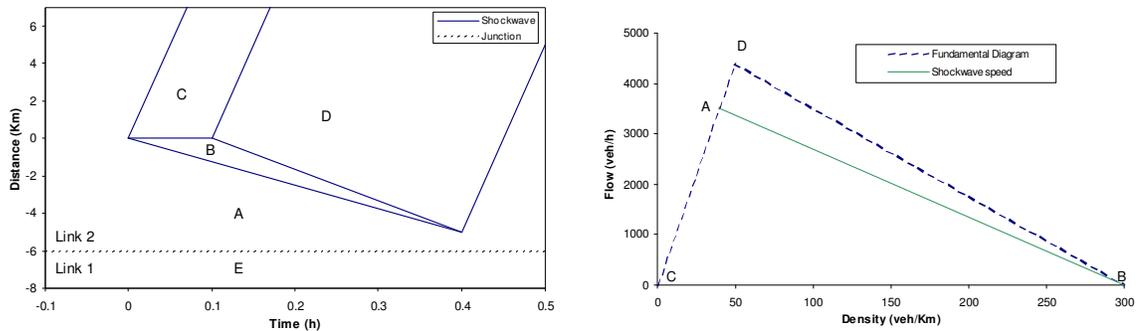


Table 2.7: Summary Traffic states for Scenario 1 (Knoop, 2009)

| State | Lanes | Flow     | Congested |
|-------|-------|----------|-----------|
| A     | 2     | $\psi Q$ | Free      |
| B     | 2     | $2rC$    | Congested |
| C     | 2     | $2rC$    | Free      |
| D     | 2     | $2C$     | Free      |
| E     | 4     | $Q$      | Free      |

Figure 2.11: Traffic states for a temporal bottleneck, Scenario 2 (Knoop, 2009)

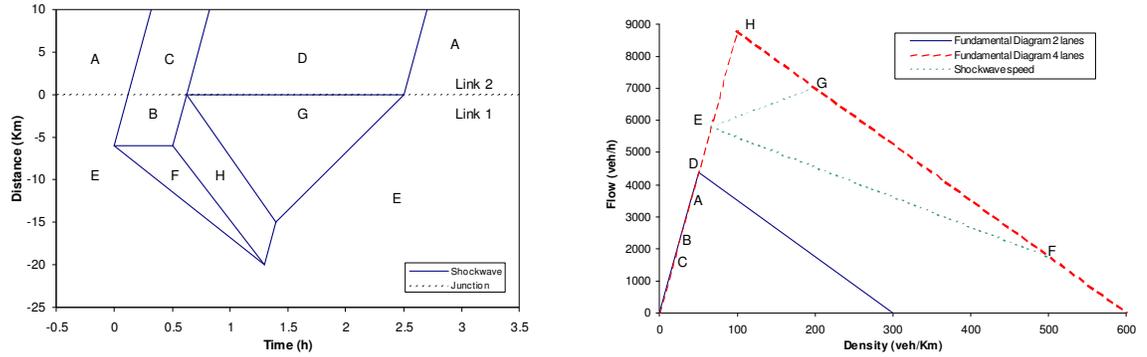


Table 2.8: Summary Traffic states for Scenario 2 (Knoop, 2009)

| State | Lanes | Flow      | Congested |
|-------|-------|-----------|-----------|
| A     | 2     | $\psi Q$  | Free      |
| B     | 4     | $4rC$     | Free      |
| C     | 2     | $4rC\psi$ | Free      |
| D     | 2     | $2C$      | Free      |
| E     | 4     | $Q$       | Free      |
| F     | 4     | $4rC$     | Congested |
| G     | 4     | $2C/\psi$ | Congested |
| H     | 4     | $4C$      | Free      |

Figure 2.12: Traffic states for a temporal bottleneck, Scenario 3 (Knoop, 2009)

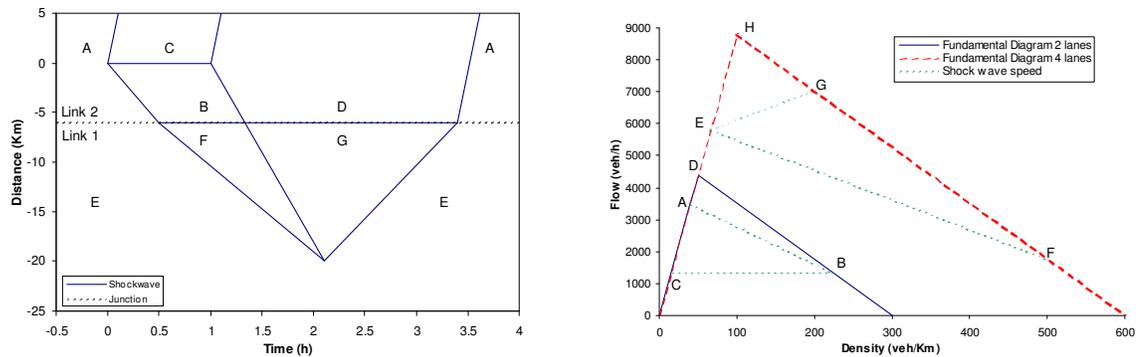


Table 2.9: Summary Traffic states for Scenario 3 (Knoop, 2009)

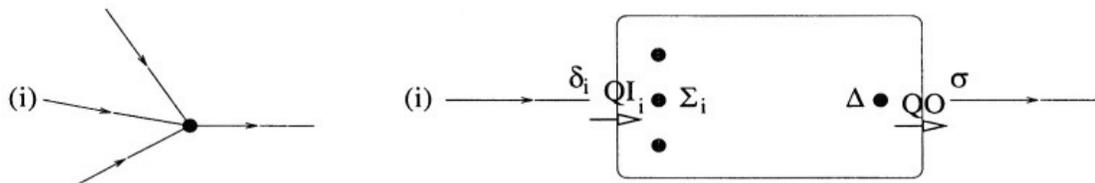
| State | Lanes | Flow       | Congested |
|-------|-------|------------|-----------|
| A     | 2     | $\psi Q$   | Free      |
| B     | 2     | $2rC$      | Congested |
| C     | 2     | $2rC$      | Free      |
| D     | 2     | $2C$       | Free      |
| E     | 4     | $Q$        | Free      |
| F     | 4     | $2rC/\psi$ | Congested |
| G     | 4     | $2C/\psi$  | Congested |

This problem is also tackled in Lebacque & Khoshyaran (2002), with another approach. Rather than considering shockwaves, their methodology is based on equilibrium between supply and demand in the intersection. Demand is related to flows that desire to cross the intersection and supply is related to its capacity.

The authors considered that solving complex optimization problems related to dynamic assignment are far too complicated and expensive (in terms of computational requirements), then they made some simplifications. For instance they considered the intersection as a single zone. In order to calculate the zone supplies and demands as a function of upstream demands and downstream supplies, they decided to calculate a stationary state of the zone, by considering the upstream supplies and downstream demands as constant. This means we consider the time-scale of the variation speed of upstream demand and downstream supply as infinitely large in regard to the variation speed of variables internal to the zone.

First, they considered the case of a merge, as presented in Figure 2.13. There, the right hand part represents the junction as a box.

.....  
**Figure 2.13: Network effects. Case of a merge (Lebacque & Khoshyaran, 2002)**



In the figure above, the meaning of the symbols is:

- $\delta_i$ : Upstream demands (flows)
- $\sigma$ : Downstream supply
- $\Sigma_i$ : Partial supplies
- $\Delta$ : Demand
- $QI_i$ : Partial inflows
- $QO$ : Outflow

Then, Lebacque & Khoshyaran (2002) approached the problem from the point of view of the supply regime (where the demand  $D$  is equal to the maximum flow through the junction  $Q_{max}$ ), and the conclusion was expressed in Equation 2.12.

.....  
**Equation 2.12**

$$QI(\Sigma) = \min \left[ \Sigma, \sum_k \min(\delta_k, \beta_k \Sigma) \right] = QO = \min[Q_{max}, \sigma]$$

Equation 2.12 may be explained as follows: the inflow  $QI$  is the minimum between the total supply (capacity upstream of the

intersection) and the sum of the inflows of every incoming link. In turn, these incoming inflows are the minimum between the demand in every link and the total supply times the split fraction  $\beta$ . At the same time, the inflow  $QI$  must be equal to the outflow  $QO$  (conservation of vehicles), which is the minimum between the maximum flow through the intersection and the downstream supply.

In case of the demand regime (where the supply  $\Sigma$  is equal to the maximum flow through the junction  $Q_{max}$ ), the conclusion is expressed in Equation 2.13:

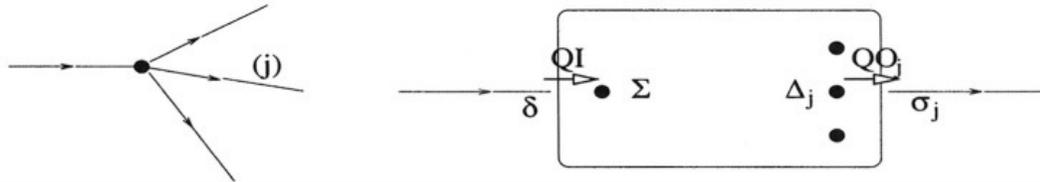
Equation 2.13

$$\min \left[ Q_{max}, \sum_k \min(\delta_k, \beta_k Q_{max}) \right] \leq \min [Q_{max}, \sigma]$$

That is, the inflow, which is the minimum between the maximum flow through the junction and the sum of the inflows of every incoming link (as explained above), should be less than or equal to the minimum between the maximum flow through the intersection and the downstream supply.

Lebacque & Khoshyaran (2002) faced the case of a diversion, which is alike to the approach of Knoop (2009) explained above, and the scheme is presented in Figure 2.14.

Figure 2.14: Network effects. Case of a diversion (Lebacque & Khoshyaran, 2002)



The methodology is the same as in the previous case, first they grasp the supply regime ( $\Delta = Q_{max}$ ) and afterwards, the demand regime ( $\Sigma = Q_{max}$ ). In the supply regime, they conclude that the outflow in every outgoing link is the minimum between its capacity and its split fraction  $\beta$  of the maximum flow through the intersection. The inflow in every outgoing link is the split fraction multiplied by the minimum between the upstream demand and the supply. It has to be noticed that in the notation used by Lebacque & Khoshyaran (2002) is confusing that they employ a symbol  $q_j$ , which is in essence the same as  $\beta$ : the split fraction. Of course the inflow and the outflow are equal, as expressed in Equation 2.14.

Equation 2.14

$$QO_j = \min[\sigma_j, \beta_j Q_{max}] = q_j \min(\delta, \Sigma) = q_j QI$$

In the demand regime, the result of the analysis is presented in Equation 2.15. The minimum between the upstream demand and the

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maximum flow through the intersection is less than or equal to the minimum of the quotient of the downstream supplies and the split fractions, for all the outgoing links.

.....  
Equation 2.15

$$\min[\delta, Q_{\max}] \leq \min_j \left( \frac{\sigma_j}{q_j} \right)$$

As it may be noticed, although these approaches presented above started from different points, they end up in similar results. The variables used are basically the same with different names, as they are tackling the same problem. It has to be said that Equation 2.14 and Equation 2.15 are used either implicitly or explicitly in Knoop (2009), and therefore results are basically the same. For instance, take a look on state G in Table 2.8, where is clear that the flow presented there ( $2C/\psi$ ) is the same than described above in Equation 2.15 (maximum flow through the intersection is less than or equal to the quotient of the downstream supplies and its split fraction). The difference is that Knoop (2009) further elaborated on the shock wave theory based on these equations, and presented the results for specific cases, whereas Lebacque & Khoshyaran (2002) stay in the general framework.

## 2.5 Conclusions

This section had the aim to search and report the state of the art in the subject studied. The starting point of the literature review was the research question and sub-questions. The theoretical background information required to answer them was gathered.

In this chapter two different approach types were evaluated to assess non-recurrent delays. Using a structured method (Multi-Criteria Decision Analysis – qualitative outranking), both approach types were appraised in light of the objectives and criteria selected for this study. It led to establish that the data driven approaches are the most suitable for the case studied, and therefore the methodology proposed has this approach.

During this review some gaps were noticed in the assessment of non-recurrent congestion. This is particularly noticeable in the practical approach, rather than in the supporting theory. The main gaps noticed in the existing methodologies to determine causes of non-recurrent delays are:

- Explicit assessment of various (more than one) causes.
- Possibility to add in the model new causes of non-recurring congestion, different to those originally considered.
- Lack of a structured methodology.
- Broad estimations based on year dataset.
- Lack of considering network effects

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All of methods reviewed have at least one of these gaps. Therefore, the new methodology must cope with all of them, improving the existing ones.

The next chapter is similar to this, given that it also includes to make a review, focusing on policies involving non-recurrent congestion.

After reviewing both traffic flow theory and policy, then the new methodology will be proposed, based on the review made in this chapter.

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## 3.Policies Review

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After the literature review made on traffic flow theory related topics, it is necessary to have a review of the policies that deal with congestion, in order to fulfill the research objective stated in the first chapter: make policy recommendations to mitigate the adverse effects of the non-recurrent congestion.

The chapter begins making a review of the social (mainly) consequences of congestion and factors affected by it. Afterwards, it is presented an overview of the existing policies to face congestion (both recurrent and non-recurrent) in the Netherlands and in other countries. The final part of the chapter outlines the specific measures undertaken in the Netherlands to handle non-recurrent congestion.

This is the base to make the policy advice that will follow the analysis of the results obtained in the methodology to assess non-recurrent congestion as well as the case study that applies it.

### 3.1 Consequences of congestion

Transportation system plays a vital role in the economical growth of most countries. As may be expected, congestion affects the transportation system causing losses in its performance, which in the end results in economical losses as well. For this reason, dealing with congestion is an important issue.

Congestion (queues and delays) imposes costs on the economy and generate multiple impacts on urban regions and their inhabitants. Congestion also has a range of indirect impacts including the marginal environmental and resource impacts of congestion, impacts on quality of life, stress, safety as well as impacts on non-vehicular roadspace users such as the users of sidewalks and road frontage properties (JTRC, 2007). Congestion hinders business attraction and expansion, and reduces the quality of life for residents (CSI and TTI, 2005).

Transportation system users have developed strategies to deal with increased congestion and reduced reliability. In the short term, there would be changes in mode, route, or departure time. Over the longer run, congestion might influence people's decisions about where to live and work. The same holds for businesses. These types of adjustments might reduce the impacts of congestion, but they still do not entirely eliminate the economic consequences for a region (CSI and TTI, 2005). The congestion impacts on several fields are explained in the following.

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### **Trucking Impacts**

Congestion entails longer travel times and less reliable pickup and delivery times for truck operators. To compensate, motor carriers typically add vehicles and drivers and extend their hours of operation, eventually passing the extra costs along to shippers and consumers. Unexpected delays may add 20% to 250% to the final good costs, depending on the product being carried (CSI and TTI, 2005).

### **Businesses Impacts**

Congestion increases the costs of delivering goods and services, because of the increased travel times and operating costs incurred on the transportation system. Less obviously, there may be other costs as well, such as (CSI and TTI, 2005; JTRC, 2007):

- Costs of remaining open for longer hours to process late deliveries.
- Penalties or lost business revenue associated with missed schedules.
- Costs of spoilage for time-sensitive, perishable deliveries.
- Costs of maintaining greater inventory to cover the undependability of deliveries.
- Costs of reverting to less efficient production scheduling processes.
- Additional costs incurred because of access to reduced markets for labor, customer, and delivery areas.

The business value of time delay and market access act together to affect the profitability and revenue potential associated with doing business in a region. When one area is affected by congestion more than other areas, the relative competitiveness of these areas also shifts. The result, then, is that businesses tend to decline or move out of areas with high operating costs and limited markets, while they locate and expand in areas with lower operating costs and broader market connections. The magnitude of these changes varies by industry, based on how strongly the industry's total operating cost is affected by transportation factors. The evidence seems to indicate that regional economies that are fostered by clusters or "agglomerations" of many interrelated firms are better positioned to counter the higher operating costs due to congestion than economies that are not (CSI and TTI, 2005).

### **Household Impacts**

Households have both financial budgets and so-called "time budgets", that are impacted by congestion. Households plan their activities around the available time budget as well as around their financial budgets. As vehicle operating and maintenance costs increase with rising congestion, the budget for some types of activities or expenditures decreases. The perceived "quality of life" of a neighborhood is diminished as well, when the safety, reliability and the convenience of the transportation system decreases (CSI and TTI, 2005).

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### **Regional Impacts**

These household and business-specific impacts have an effect on regional economies. Diminished cost competitiveness and market growth opportunities are equivalent to a reduced ability to retain, grow, and attract businesses. Additionally, the redistribution of business and household activity to outlying areas and the direct delay for trips that are not diverted or otherwise changed both lead to decreases in air quality, increases in public infrastructure investment requirements, and potential impacts on health and quality of life factors (CSI and TTI, 2005).

## **3.2 Current Policies**

This section has the intention to make a review of the current situation of the policy development in the Netherlands and in other contexts. They are the basis for the policy recommendations that will be given in this thesis later on, in chapter 6.

As mentioned before, congestion causes negative impacts on society, by losing scarce and valuable resources such as energy and time, and causing other undesirable effects such as environmental damage. For that reasons, it sounds logical that society attempts to manage it. The first step to do so is to understand it, looking for its sources. It implies to decompose congestion (expressed in terms of delays). Assessing congestion composition includes identifying those causes that have the largest consequences, making it possible focusing on the most critical aspects to reduce or even solve congestion.

### **3.2.1 Policies in the Netherlands**

The current policy in the Netherlands to cope with congestion is referred to as '3B Policy'. The slogan of this policy is "A choice for innovation". It was set up in 2001 and it is intended to last until 2020. The main intentions of this policy are to allow mobility, to use existing infrastructure more efficiently, to build new infrastructure where necessary, to price the consumer for what the road-user actually uses and to implement new technology. The 3B stands for the three strategy components that begin with B in Dutch: *Bouwen* (Building), *Beprijzen* (Pricing), and *Benutten* (Efficient use). The non-recurrent congestion falls therefore within the third strategy. The three strategies are elaborated in the following.

#### **Building**

In 2003 a legislation<sup>4</sup> was released designed to accelerate road-widening schemes, and several widening projects were approved on motorways. The extra capacity was added to existing bottleneck areas. Additionally, other new construction projects were planned, even up to 50 years ahead. Although it is very effective, it is expensive as well and it takes a long time (RWS, 2009).

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<sup>4</sup> in Dutch: *Spoedwet wegverbreding*

### Pricing

In 2007, the Dutch government decided to introduce road pricing to improve accessibility and the quality of the living environment. The price charged will depend on the time and place of driving and the environmental characteristics of the vehicle. This approach was chosen since the payments are based on the vehicle use instead of ownership of the vehicle. The intention is that road pricing will be introduced at the beginning of 2012, starting with freight vehicles. Later that year, all passenger cars will make the transition step by step, until road pricing is fully implemented in 2017. Albeit this is a promising strategy, it is politically difficult (RWS, 2009).

### Efficient use

The last strategy is also known as traffic management, and it is effective, flexible, less expensive than the other strategies presented, and fast to implement (RWS, 2009). The enhanced use of existing infrastructure is one of the key instruments in the Dutch traffic and transport policy. The government would like to improve the road use efficiency and use as much as possible the current road capacity. A better efficiency could be achieved by implementing ITS in vehicles or alongside/above infrastructure as proposed by the policy.

The summary of traffic management measures undertaken in the Netherlands can be found in Table 3.1.

Table 3.1: Summary of the traffic management measures in the Netherlands (RWS, 2009)

| Measure                       | # Locations | # Kilometres |
|-------------------------------|-------------|--------------|
| Monitoring                    |             | 2628         |
| Cameras                       | 1494        |              |
| Motorway management           |             | 1179         |
| Speed measures                | 5           | 20           |
| Ramp-metering                 | 99          |              |
| Overtaking prohibition trucks | 82          | 1100         |
| Hard-shoulder lanes           | 25          | 135          |
| Bus/Freight lanes             | 12          | 24           |
| Measures for buses            | 88          |              |
| Traffic signal control        | 257         |              |

The overview of the most important effects obtained with the traffic management measures adopted in the Netherlands is resumed in Table 3.2.

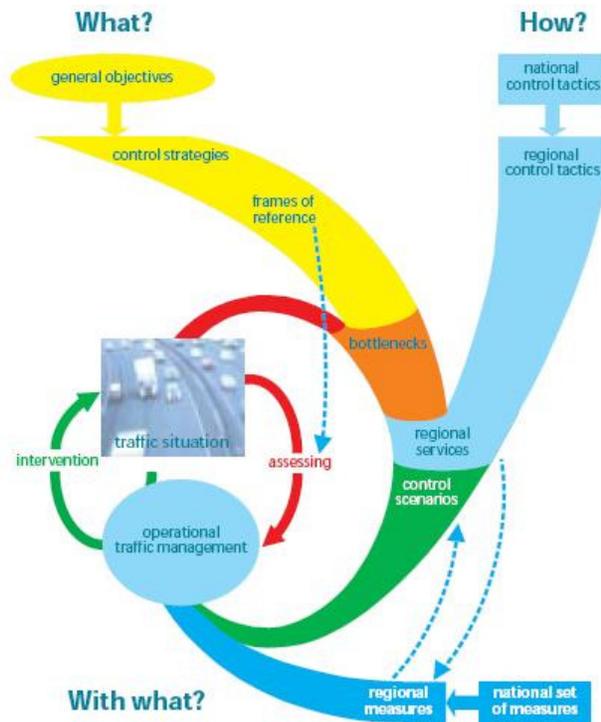
Table 3.2: Overview effects of traffic management measures in the Netherlands (RWS, 2009)

| No. | Measure                            | Effect on traffic   | Effect capacity |
|-----|------------------------------------|---|-----------------|
| 1   | Motorway Traffic Management System | Flow improvements 0% - 5%   | 0% to 5%        |
| 2   | Speed Measures (80 km/h zones)     | Congestion varies from -40% to +50%                                       | -9% to +4%      |
| 3   | Ramp Metering                      |   | 0% to +5%       |
| 4   | Overtaking prohibition trucks      | Different per location  | -4% to +4%      |
| 5   | Peak lanes (using hard shoulder)   | Decrease travel times from 1 to 3 minutes<br>Extra traffic from 0% to +7% | +7% to +22%     |

| No. | Measure                                  | Effect on traffic  | Effect capacity |
|-----|--|--|-----------------|
| 6   | Bus lanes, truck lanes, tidal flow lanes | Travel time busses/trucks -14 minutes<br>Travel time other traffic from -5 to +2 minutes |                 |
| 7   | Measures for Roadworks                   | Less demand, sometimes to -11%<br>Less traffic on the section with road works: to -38%   |                 |
| 8   | Traffic Signal Control                   | Change in travel times from -33% to +10%   |                 |
| 9   | Other measures                           | Congestion from -28% to +45%   |                 |
| 10  | Incident Management (camera's)           | Congestion -7% (Utrecht)   |                 |
| 11  | Dynamic Route Information Panels (VMS)   | Congestion from -7% to -30%  |                 |
| 12  | Radio Traffic Information                | Route changes, more change if travelers are informed individually                        |                 |

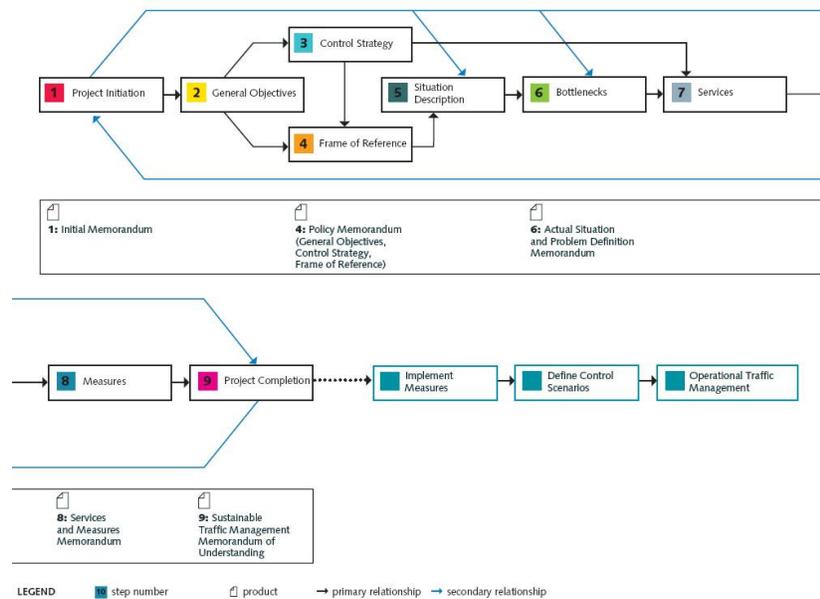
In a more general framework, the strategies on traffic management (efficient use), which are the 3rd component of the policy to tackle congestion, are contained in the Handbook Sustainable Traffic Management (RWS, 2003). This handbook encloses the Traffic Control Architecture process (national level) of the Traffic Management Architecture, which has been conceived as a corkscrew model, shown in Figure 3.1. The model illustrates how forces and input arrive practically simultaneously from different directions. In a converging and cyclic process, they eventually result in operational traffic management with a balanced set of traffic control measures. The model covers the entire process, from the initial intent to improve the local traffic situation right up to an integrated traffic management concept.

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 Figure 3.1: Corkscrew model Traffic Control Architecture process of the Traffic Management Architecture (RWS, 2003).



The Handbook Sustainable Traffic Management (RWS, 2003) explains the way to develop a new Traffic Management measure, within the reference framework presented above. It is made in a nine-step process, shown in Figure 3.2.

Figure 3.2: The nine-step process of traffic management (RWS, 2003).



As it may be seen, the existing policies do not deal with non-recurrent congestion explicitly, apart from the measures for roadworks (Table 3.2). This includes avoiding to work on roads during rush hours (as far as possible), planning roadworks to perform them during holidays, and to avoid overlapping catchment areas of the works. The rest of the measures mentioned in Table 3.2 could be used for both recurrent congestion and for non-recurrent cause of congestion incidents. For adverse weather conditions, the measures taken are related with changes in the speed limits (if the rain is heavier than 6 mm/h, then the speed limit drops to 80 Km/h), but this is more related with safety issues than with dealing with congestion.

With the purpose of comparing the mentioned policies with those proposed in a broader framework, the policies developed in the 'European context'.

### 3.2.2 Policy in European context

The European Conference of Ministers of Transport presented the policies for a European context in JTRC (2007). They state that fully eradicating roadway congestion is neither an affordable, nor a feasible goal in economically dynamic urban areas. However, much can be done to reduce its occurrence and to lessen its impacts on roadway users: congestion is a phenomenon that can be better and more effectively managed. Effectively managing congestion requires both a complete and integrated strategy that goes beyond the visible incidence of congestion "on the road" and extends to the management of the

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urban region as a whole. It includes urban planning and the general transport master planning process, since roadway congestion impacts not only road users but also all urban inhabitants. The paper suggests a policy reference framework (called strategic congestion management principles), rather than specific congestion management measures. Those strategic congestion management principles are described in the following.

**Ensure that land use planning, and the community objectives it embodies, is coordinated with congestion management policies**

Coordinated transport and land use policies allow to proactively and beneficially manage the scope and nature of travel demand and thus reducing the incidence and severity of congestion. These two fields are quite correlated as land uses induce trip generation and the interaction between origins and destinations yield regional trip patterns. Experience from a number of countries and regions has shown that well-thought out land-use policies that explicitly link community expectations to the long-term development of the transport outcomes can have a positive impact on a number of consequences, including traffic and congestion management.

**Deliver predictable travel times**

Congestion has an impact on both average travel speed and travel time reliability. As it was mentioned at the beginning of the chapter, reliability of travel time is an important issue for road users. This finding has been supported by studies that have found that the value of reliability to road users is in many cases higher than their values of travel time. Typical measures include planning and coordination of roadworks, speedy response to defective traffic signals and to disruptions caused by accidents and debris (non-recurrent causes of congestion).

**Manage congestion on main roads**

At present, access to roads is generally unconstrained by everything but congestion itself. Indeed, congestion is a powerful rationing mechanism (scarcity of road space and unreliable travel times) but few would agree that is efficient. There are mainly two congestion management strategies: those that provide new capacity and those that restrict, limit, or manage traffic levels.

The latter category of measures broadly encompasses three different but related approaches:

- Directly managing the physical access to the roadway through access policies. Access policies seek to restrict vehicle access to certain zones (e.g. historical centers) or to certain road links (ramp metering).
- Indirectly managing access to the roadway network and directly influencing road travel to particular areas through parking policies. Parking management and control can assist the task of tackling

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traffic congestion by reducing the demand for travel to the area encompassed. Due to the considerable policy and operational flexibility available, parking control can also be quite specifically targeted, in the sense that it can be applied on the basis of location and time.

- Managing the level of traffic through road pricing policies that target the use of, or access to, roads or urban areas. Pricing policies include cordon charges such as those implemented in Singapore, London and Stockholm and link-based pricing systems such as those that have been put in place on certain urban tollways, and mixed-use toll roads (e.g. HOT Lanes in the United States). All have proven to be effective measures to reduce congestion and manage traffic. While their effectiveness is difficult to question, implementation has proven to be challenging. Equity is a very important consideration. Even if the proceeds of the congestion charges are redistributed to road users, in the form of lower fuel taxes for instance, a congestion charge is likely to benefit people as a function of their values of time. Road users as a group gain but some gain much more than others.

Besides those strategies, the paper also proposes further strategies, which they called 'more effective in tackling congestion than in the past'. These additional strategies (explained below) look to complement those mentioned above, looking to make them sustainable in the long-term run, reducing congestion.

#### **Improving traffic operations**

Road traffic information systems, pre-trip guidance, coordinated traffic signal systems and the implementation of dynamic speed and incident management policies have often proven to be cost-effective ways to deliver better travel conditions, allowing users to reschedule their trips away from traffic peaks and/or select other travel modes. These strategies all allow road managers to get more out of roads – e.g. to allow for greater flows than could otherwise be realized.

#### **Improving public transport**

Public transport has the potential to transport more people than individual cars for a given amount of road space (in the case of on-street systems such as buses and trams) or without consuming any road space at all (in the case of off-road systems such as metros and surface rail systems). The promotion of public transport remains a fundamentally important congestion management strategy. When public transport provides a quality of service that approximates that which car drivers have previously been used to, it can maintain a high level of accessibility with a drop in overall car usage. Those measures should address actions to encourage a mode shift to public transport, such as the perceived costs by the user, ease and comfort of traveling by public transport as well as its reliability, safety and security.

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### **Implementing mobility management**

There are numerous mobility management strategies that can, when successful, reduce car use in urban areas. These include ride sharing, promoting bicycling and pedestrian travel or supporting mobility management efforts targeting large trip generators such as companies.

### **Modifying existing infrastructure**

There are many approaches that can squeeze additional capacity out of existing infrastructure. These include adding lanes, re-allocating road space, modifying intersections, modifying the geometric design of roads or creating one-way streets. These approaches can benefit either car users or public transport. While these types of measures are ideally suited for treating bottlenecks, care should be given to consider the downstream impacts of releasing greater traffic flows through previously contained bottlenecks. Great care should be taken to at least address what the network effects will be over the mid- to long-term.

### **Building new infrastructure**

Building new road infrastructure is often constrained by a lack of space in dense urban cores and is nearly always an expensive proposition. Many cities now view infrastructure expansion only as a last resort. The effectiveness of providing new road capacity as a congestion management “solution” is oftentimes eroded by new traffic demand. However, there are instances where the provision of new infrastructure is an effective policy – especially when subsequent demand for the infrastructure in question is actively managed as in the case of toll roads and HOT lanes. The decision to invest in new road capacity (or parking capacity) should be motivated by a thorough cost-benefit exercise that addresses the wide range of congestion impacts detailed earlier.

### **Are institutional arrangements encouraging or discouraging appropriate responses to congestion?**

Typically, congestion cuts across jurisdictional boundaries and therefore congestion management requires collaboration between different authorities. At the national level, it is important that policies make coordination between regional transport and urban planning bodies legally possible, and encouraged. This includes the design of funding mechanisms.

### **The right combination of policies**

It includes:

- Understanding what congestion is and how it affects the urban region.
- Developing and monitoring relevant congestion indicators.
- Intervening to improve the reliability of travel time, to release existing capacity or to provide new infrastructure.
- Managing demand for road and parking space consistent with a shared vision on how the city should develop.

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As it may be seen, this a broad range of measures, and as it may be presumed, it involves a variety of fields and institutions, in the same manner road traffic is correlated with all of them.

### **3.3 Strategies to Mitigate Impacts of Non-Recurrent Events**

As one might expect, strategies have been designed to mitigate the negative impacts that non-recurrent events have on motorway operations. In the Netherlands, these kinds of strategies have been created, concentrated principally in Roadworks traffic management and Incident Management IM. They are described in the following.

#### **3.3.1 Roadworks**

Calvert (2009) states that the general framework for mobility management for roadworks is contained in Handbook Mobility Management for Roadworks. Among other things, this book determines the severity of roadworks nuisance and sets out mitigating measures and the methods of communication with the road users as well. This book defines Mobility Management as "Organizing smart travel" (Calvert, 2009). In the light of this strategy, the generic project approach for planning roadworks should follow the next steps:

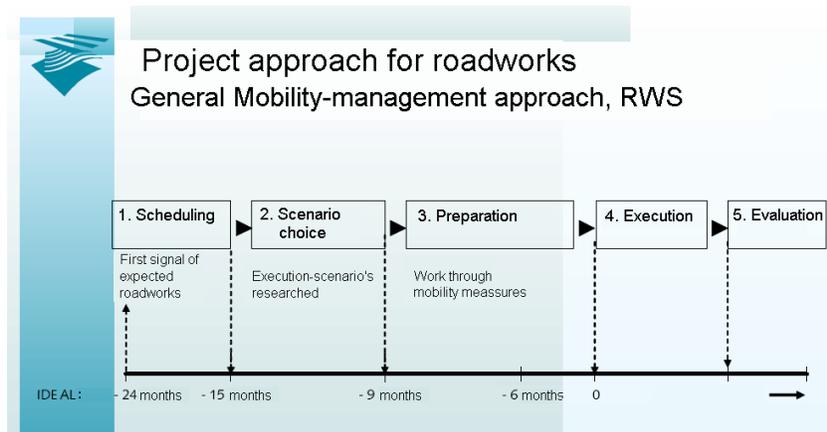
1. Initiation and initial planning of works (Preliminary Mobility Plan): it includes: establish nuisance class, time framework (Period), overall length and size of roadworks, and gross nuisance (expected that the additional nuisance caused by the work).
2. Preparation and scenario-planning: it includes the civil engineering works planning. In mobility plan, this step involves traffic and mobility plans, and intended net nuisance value.
3. Roadworks preparation: Further identification and elaboration in developing traffic and mobility management measures.
4. Roadworks Implementation: The roadworks start. It includes rule scenario execution and monitors traffic behavior since the beginning, to adjust the undertaken measures, if necessary.
5. Project evaluation: Ex-post assessment of the measures undertaken, the actual congestion levels, and communications.

Figure 3.3 shows the approach for planning roadworks schematically, coupling the five steps with the (indicative) time axis and indicating the main actions that are involved in every step. In the figure, "time 0" means the start of the roadwork implementation (Hazelhorst & Munck, 2007).

As it was noticed, the processes of establishing nuisance levels and communication with users occur during the first 3 steps. For instance, the capacity reduction due to roadworks is calculated in steps 1 and 2, and initial measures to mitigate it are proposed. These calculations are estimations of changes to the capacity of a road, using official

directives and software tools, and estimates of possible changes to the traffic demand.

Figure 3.3: Roadwork planning approach in the Netherlands (Calvert, 2009).



At an early stage, and often up to a year before the commencement of the works, the public is informed about the works with an indication of the expected nuisance. These estimations are improved as long as more details about the roadworks are available. Finally, the nuisance level of the project is established. The nuisance levels with their different categories (A to E), the expected delay caused either by congestion or detours (classes 0-4), and the estimated number of vehicles affected by the roadworks, are presented in Table 3.3. The nuisance classes are used by road authorities to determine the level of action that is needed to counteract the effect of delays and is further used to communicate with road users.

Table 3.3: Nuisance Classes and Categories (Hazelhorst & Munck, 2007)

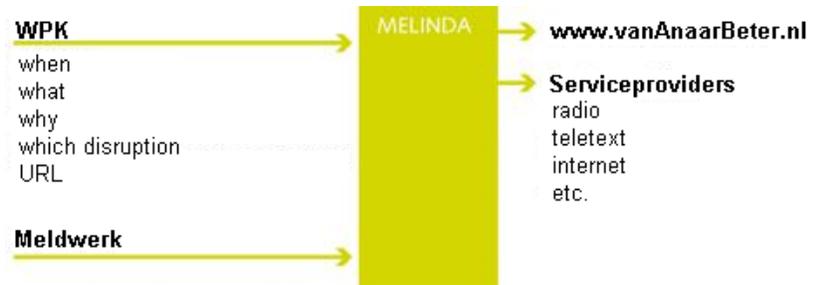
|                    |                                   | Road users affected |         |          |     |     |
|--------------------|-----------------------------------|---------------------|---------|----------|-----|-----|
| Nuisance Class     | Delay/Diversion                   | <1.000              | <10.000 | <100.000 | <1M | >1M |
| 0 no nuisance      | -                                 | -                   | -       | -        | -   | -   |
| 1 small nuisance   | < 5 min. / no traffic jam         | E                   | E       | D        | C   | B/C |
| 2 some nuisance    | 5-10 min. congestion / diversion  | D                   | D       | C        | C   | B   |
| 3 much nuisance    | 10-30 min. congestion / diversion | C                   | C       | B        | A   | A   |
| 4 extreme nuisance | >30 min. congestion / diversion   | B/C                 | B       | B        | A   | A   |

| Category | Description                     |
|----------|---------------------------------|
| A        | Extremely large works           |
| B        | Large works, non-national scale |
| C        | Medium works, regional scale    |
| D        | Small works                     |
| E        | Small closures                  |

With regard to communication with road users, it is done in a number of ways. For instance, in the Rijkswaterstaat webpage ([www.rijkswaterstaat.nl](http://www.rijkswaterstaat.nl)) there is information about planned roadworks

in the coming days and nuisance levels. In 2006, the system MELINDA was set-up to coordinate information flows about roadworks between the road authorities and service providers. This means information is collectively gathered and forwarded to the service providers. The general communication process is shown in Figure 3.4 (Calvert, 2009).

Figure 3.4: Information flow for major roadworks on highways in the Netherlands (Calvert, 2009).



Road authorities utilize nuisance classes indicator to estimate the level of action required to tackle the adverse effects of roadworks (such as delays) and communication level with road users. This ‘level of action’ refers to traffic management measures undertaken (amount and intensity), and they are often intended to reduce the traffic demand in the corridor where the roadworks take place. For instance, a traffic management measure may include encouraging the use of public transport by means of (low) price incentives (Calvert, 2009). It also may entail to deviate road users to alternative routes, changing departure time choice or even avoiding to make trips, which are network effects.

### 3.3.2 Incident Management (IM)

Incident Management strategies began in the Netherlands approximately on 1995, and since then, it has been continuously improved to become a regular national practice in the main motorways network (Knibbe, 2004).

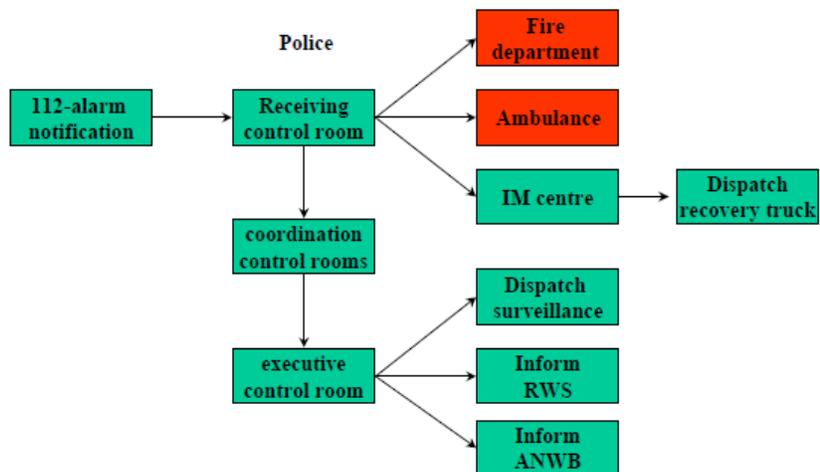
According to Adams (2008), the Incident Management in the Netherlands is defined as “the set of organizational and technical measures designed to clear the road for traffic as soon as possible after an incident has happened, besides protecting the interests of possible victims, the safety of aid workers, the road safety, as well as controlling the damage caused and traffic flow”.

The IM policies are mainly focused in the organization around an incident, in order to improve safety (road, people, et cetera) and traffic flow. The main two pillars of IM in the Netherlands are National Passenger Car Rule<sup>5</sup> and National Truck Rule<sup>6</sup>. These rules were created to organize and speed up the removal process of crashed vehicles from the road, and then reducing the incident duration time (Knibbe, 2004). The general process of the car rule is presented on Figure 3.5.

<sup>5</sup>In Dutch: *Landelijke personenautoregeling LPR*

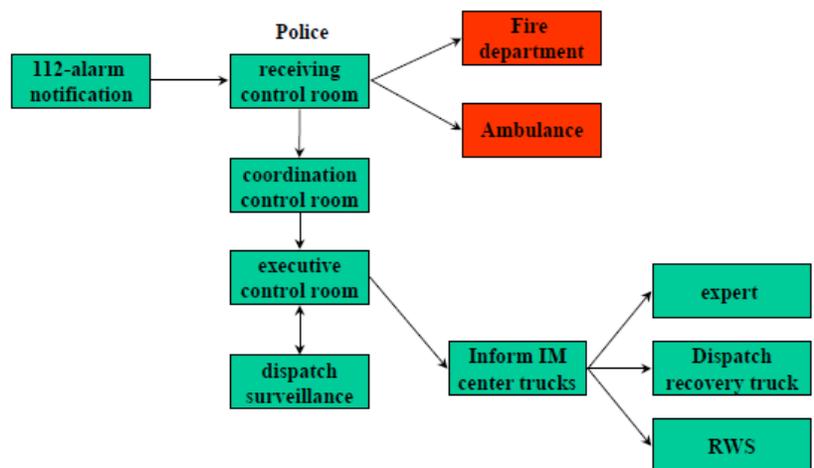
<sup>6</sup>In Dutch: *Landelijk vrachtautoregeling LVR*

Figure 3.5: Alarm procedure for incidents involving only passenger cars (Knibbe, 2004).



Usually an incident warning call is made to the alarm phone (normally answered by the police), where they inform RWS and *Koninklijke Nederlandse Toeristenbond* [ANWB]. In case of the incident require ambulance or further services, they are also called. They inform as well the national IM center, which immediately send a tow truck to the incident location. The procedure is basically the same for trucks (truck rule), which is presented in Figure 3.6.

Figure 3.6: Alarm procedure for incidents involving trucks (Calvert, 2009).



The difference between both rules (cars and trucks) lies in the fact that trucks have different sizes and any kind of cargo that may require specialized equipment to handle. Therefore, when trucks are involved in incidents, the IM center for trucks is informed after the police arrives and evaluates if some special equipment is needed.

Besides these two main measures, there have been implemented another IM measures in the Netherlands (Adams, 2008):

- The IM+ project. Rijkswaterstaat road inspectors get more power on the road incident location, such as controlling the traffic.

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- Enhancing the understanding of the quality of the IM helping process by means of the initiative "ICT Incident Management Information System".
  - Regional Incident Management: Introduction of provincial and municipal roads in IM process.
  - Integration of IM Project in VCNL.

In addition, some measures and projects have been implemented outside the IM policy, in the ITS field (Adams, 2008):

- Variable Message Signs (VMS) and video monitoring.
- Warning system for slippery road surface or wind,
- In-car systems (e.g. intelligent cruise control system).
- Integrated Network Management measures.

In order to contextualize the Dutch IM measures, it is necessary to contrast them with those similar measures undertaken in other European countries. For instance, the United Kingdom created an agency, the National Traffic Control Centre [NTCC] (Highways Agency, 2010). This agency plays a role as the operator of the UK's motorway and trunk road network, and its main objective is to inform travelers, and so helps improve journey reliability. They are in charge of handling non-recurrent events, which they divide in 'planned' (roadworks, special events), and 'unplanned' (mainly incidents). Therefore, in the last lie IM measures, which follow the next procedure (Highways Agency, 2010):

- Receive alert: From traffic sensors or an operational partners.
- Gather information: Check sensors and talk to operational partners to confirm the situation.
- Validate reports/readings: Confirm whether the alert is accurate
- Create Event: if the alert is confirmed, then an Event is created to capture the place, time and likely duration of the incident. This information is used to create public announcements on the website, telephone service, Variable Message Signs, and media alerts, automatically.
- Select best response plan: Taken into account current traffic flows, other events (that may compound the incident), impact on diversion routes, and planned events in the area, proposes response plans to offer road users the best way out. An Operator takes the final choice between plans.
- Implement plan and communicate: Chain of actions: alerting the media and ITS service providers, updating websites, and setting VMS signs.
- Monitor effects and change plan: Watch for changes, and modify the plan in case it is required.

In the case of Belgium, IM is approached in a very similar way to the Netherlands. Normally the first action is an incident report received at the call center of the highway police. Then, the highway police dispatch a unit to the incident location. They make the decision to call in a tow

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service in case it is required. Additional help services (fire department, ambulance services) are called either when the police unit at place ask for it, when the roadside cameras indicate so, or if the original caller reports the situation as serious. In the case of severe accidents a representative of the public prosecutor has to investigate the scene before the police can reopen the road (Geodan, 2008).

The approach is aimed at handling an incident on the spot. The fact that the police must always be dispatched to an incident leads to time loss. On the busy roads around cities, this time loss was deemed too large because of the congestion it causes. To prevent this situation, to improve response times and to minimize impacts on traffic flow, it was implemented a project called FAST on the ring roads around Brussels, Antwerp and Gent. FAST stands for *Files Aanpakken door Snelle Tussenkomsten*. This project contemplates to locate a number of tow trucks (one to three) around the ring roads. When an incident occurs the tow trucks are immediately directed to the location of the incident. The police mark the locations of the vehicles and carry out the investigation. The vehicles are towed off the highway as soon as possible, and they are transported to the nearest exit where they are transferred to another tow service. This ensures that the FAST tow service is back available on the ring road quickly after handling an incident (Geodan, 2008).

In order to improve communication between emergency services Astrid was set up. Astrid is a telecom operator specifically meant for emergency services. It operates 11 provincial control centers where incoming calls are handled and dispatched to services. Astrid is aimed at optimizing communication between the different emergency services (Geodan, 2008).

### **3.4 Conclusions**

In this chapter the existing policies that deal with congestion were reviewed. Clearly, in the same manner as in the previous chapter, this one starts from the research questions and objectives of this study. Based on this the subjects to evaluate were selected.

It could be seen that most of the European guidelines are already included in the policies in the Netherlands. Comparing these two approaches, it can be seen that in efficient use are included manage congestion on main roads, improving traffic operations, and mobility management. Building includes modifying and construct new infrastructure. However, there is a point of the European guidelines, which does not clearly appear in the policies in the Netherlands to tackle congestion: improving public transport, as an alternative mode for personal car. It is considered that it should be closer to the core of the policies aimed at diminish congestion.

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In this chapter could be seen that in the current practice in the Netherlands, various strategies are implemented to deal with roadworks and incidents as causes of non-recurrent congestion. In the roadworks case, they should be framed in a 5 steps plan, which include from the first signal of the roadwork expectations to the ending of the actual works. This process may take some years, and it has strengths like the developed indicator, the so-called nuisance level. It is aimed at measuring the hinder that the roadworks cause and the idea is to design a contingency plan that sets the indicator as low as possible.

With regard to incident management IM measures in the Netherlands, it is the result of several years of experience. Comparing with other European countries, it has similar structure with a call center that centralize the calls and it starts the salvage procedures, evaluating if further (emergency) services are required, and intending to clear the road as soon as possible, maintaining always high security levels. IM measures in the Netherlands have advantages (comparing with other countries) like separating a plan (and therefore procedures and actions) for personal vehicles and trucks. However, in the United Kingdom the IM services are integrated with ITS services, that is, they belong to the core of the measures. In the Netherlands ITS services are not in the core of the IM measures.

These measures have influenced traffic operations, and they have already decreased negative impacts of non-recurrent occurrences such as incidents and roadworks, comparing with the situation with no plans implemented. Nonetheless, RWS lacks of measures that explicitly intend to tackle adverse weather conditions. Therefore, these facts give the opportunity to fill the mentioned gap in this work, which is going to be done in the following chapters.

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## 4. Methodology to Assess Delay Components

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The literature review described the background of the concepts, methodologies and considerations required to assess non-recurrent congestion. There was also concluded that in this research a data driven approach will be used.

These are the starting points to develop a methodology to decompose the delays in its diverse parts and to assess them. This step is the accomplishment of the main research objective. This process is based on already existing methods, but the outcome is a new proposal that fill the gaps of the methodologies mentioned: explicit assessment of various causes of non-recurrent congestion, include network effects, possibility to include in the model unconsidered causes, and a more structured and accurate tool to assess non-recurrent congestion. This chapter involves solving the research questions 1, 2, and 3.

The chapter begins describing the data collection process to give an insight into the way in which the data are obtained. In the following the description of the available data sources is found, along with the process of checking (and correcting) them. Afterwards, these data are used as an input to assess the non-recurrent congestion. This is done in the next part of the chapter, which is devoted to the methodology itself, explaining in detail all the steps comprised. The next part of the chapter is focused in giving an insight into the computer tool developed to automate the developed methodology. The closing section of this chapter is focused on the validation of the developed methodology, in order to prove if its results are satisfactory.

After this chapter, the following step includes using the developed method on real cases data.

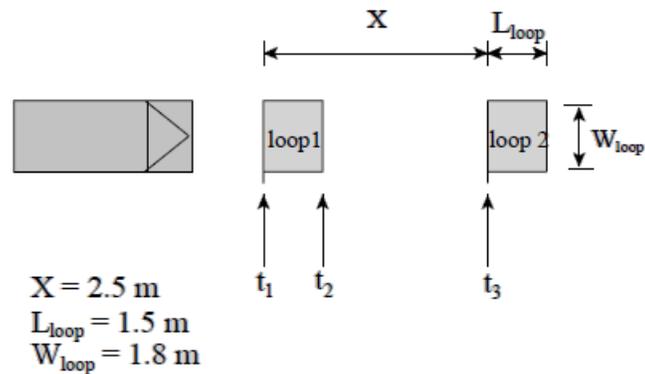
### 4.1 Data collection

Since the main objective of this study is to assess non-recurrent congestion in the Netherlands, it is necessary to obtain real data from the Dutch motorways. For that reason, it is important to have an insight into the way these data are collected. According to Hall (2001), five main measurement procedures exist.

- Measurement at a point (cross section).
- Measurement over a short section (length less than 10 m).
- Measurement over a span of road (length usually at least 0.5 km).
- Use of an observer moving in the traffic stream.
- Wide-area samples obtained simultaneously from a number of vehicles, as part of Intelligent Transportation Systems (ITS).

As it may be expected, the procedure used depends on the data required and the available measurement technique. Considering the existing measure methods in the Netherlands, then it was decided to focus this section on the measurements at a point (cross section). The most employed techniques to do so are manual (using a form and a stopwatch), pneumatic tube, inductive loop technology, microwave, radar, photocells, ultrasonics, and television cameras (Hall, 2001). Inductor loops detectors are the measurement technique further elaborated, as it is the most often used in The Netherlands (van Lint, 2009). It consists of loops that are buried in the road surface, which measure changes in magnetic fields as vehicles pass. The induced voltage shows alternately a sharp rise and fall, which correspond approximately to the passing of the front of the vehicle over the front of the loop and the rear of the vehicle over the rear of the loop. A scheme of the induction loop detector measurements is presented in Figure 4.1 (Hoogendoorn, 2007).

.....  
**Figure 4.1:** Loop configuration as applied on Dutch motorways (Hoogendoorn, 2007)



When two loops are installed behind each other on a lane (a 'trap'), it is possible to determine for each vehicle the passing moment, speed, and vehicle length. On Dutch motorways it is customary to use two loop detectors as presented in Figure 4.1, implying that in principle, individual vehicle variables are available. The mathematical relationship between individual speed  $v_i$ , vehicle length  $L_i$ , and different variables shown in the figure are (Hoogendoorn, 2007).

.....  
**Equation 4.1**

$$v_i = \frac{X}{t_3 - t_1} \quad L = v_i (t_2 - t_1) - L_{loop}$$

In this way, it is also possible to measure the flow rate  $q$  as the number of vehicles  $N$  passing the induction loop during a given time interval for traffic variables  $T_{avr}$ , as well as the gross time headway ( $h_i$ ) (difference in passing times).

With these data it is possible to obtain directly the time mean speed  $u_L$  (sum of the vehicle speeds divided by number of vehicles), yet it is more appealing to use the space mean speed. Time averaging does not only lead to overestimated speeds, but it also leads to biased estimates

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of all traffic quantities that propagate over space (van Lint, 2009). Consequently, in this study the space mean speed  $u_M$  will be used in calculations.

To do so, it is necessary to average the quantities over space. Hoogendoorn (2007) and van Lint (2009) demonstrate that the space mean speed could be obtained as the harmonic average of the speeds collected at a cross-section  $x$  during a stationary period, as follows:

.....  
Equation 4.2

$$u_M = \frac{1}{\frac{1}{n} \sum_{i=1}^n \frac{1}{v_i}}$$

It is denoted that under the assumption of stationary and homogeneous traffic conditions, the harmonic mean speed at a cross section equals the space mean speed over that section. However, this is an idealization, and harmonic mean provides an approximation for the space mean speed (van Lint, 2009).

## 4.2 Data Sources

The data are collected in the Netherlands, from the double induction loop detectors, described in the previous section. The road data collected consist mainly of flows and speeds, as was described before. The information collected by these detectors is stored in databases, which are input for this work.

This section describes first the data sources that will be used in the research. Since data from most types of traffic sensors are noisy, faulty, and to a degree unreliable or even completely missing (van Lint, 2009), it needs to be checked and corrected, as presented in the second part of this section.

### 4.2.1 Sources

Within this project the following databases are available and will be used. They are classified according to their content, in the following:

1. Traffic Jams: Monica: Database with locations, traffic data, road number, per hectometer of road.
2. Roadworks: Currently there are two databases: WPK and Meldwerk which are going to merge into SPIN. They belong to VCNL.
3. Incidents: IM Database, which has information per hectometer of road.
4. Meteorological info: Koninklijk Nederlands Meteorologisch Instituut (KNMI). It contains weather information per road kilometer.

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In these databases the precise sample data have to be selected (single events). The defined non-recurrent congestion causes (incidents, roadworks, and adverse weather conditions) are sought in databases .

The mentioned Monica, WPK, and IM databases are already available for the motorway network, in most parts of the country. This is not the case for the weather database, where the available information is the Doppler radar reflection, captured for the whole country. These data can be correlated with rain intensity, measure in millimeters of rain per hour (mm/h). It was already developed a method to correlate the satellite information with the motorways hectometers. However the database that correlates rain with motorways stretches (hectometers) not exists as such. Hence, it has to be built for this case, selecting the data for the period and the area under study.

#### 4.2.2 Data Checking

In case of the data collection by sensors, data failure is the occurrence of unreliable (noisy) and/or missing data from a stream of data coming from traffic sensors. This happens when a sensor produces data that are dubbed unreliable (either by the modeler or the device itself), or when it produces no data at all (van Lint, 2009).

Data checking and correcting encompasses the following (usually iterative) steps (van Lint, 2009):

1. Data (consistency) checking: before possible problems (e.g. missing or faulty data) can be adequately tackled, they need to be detected first. It would be done using conservation of vehicles or mass-balance, visually checking spatio-temporal patterns in the data, and statistical procedures.
2. Data completion: filling the possible gaps in the data with reasonable replacements and correcting the resulting complete data set. The methods for local data correction which are often applied in practice to correct traffic data are: Imputation methods (interpolation and smoothing) and filtering methods (using traffic characteristics).
3. Back to 2 until satisfied

Since it is necessary to correct the data before use it, then is it is required to use data checking and completion methods. Nevertheless, among the objectives of this work are not to enhance these methods. Therefore, the theory behind them is not further elaborated. It only has to be mentioned that to accomplish this procedure, one of the existing models will be used. After considering the existing methods to check and correct the data, it was decided to use a Treiber-Helbing filter method, developed by van Lint (2009). This filter combines two anisotropic low-pass filters, one for congestion and one for free-flow conditions, using a weighting factor  $w(t, x)$ , which determines the weight of each of these two filters. The data are ready to use after the filter is applied (van Lint, 2009).

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In like manner, the data coming from the databases mentioned in previous section could be unreliable in certain extent. It depends on the quality of its registration. Naturally the quality of the results obtained depends on the quality of the inputs.

For instance in the case of roadworks, In Chapter 3 it was noticed that often they are the result of a careful planning process from the conception until the tendering and assign contracts. Consequently, it is possible to know very accurately beforehand most of the roadworks locations (in time and space) that would be undertaken in the main motorway infrastructure. So, this database is considered to have a high reliability and need no further corrections.

Considering the accuracy of the weather information, it is based on weather radar reflection. This method is deemed quiet truthful and therefore its info can be used with no corrections.

The last database considered was the incidents one. The Netherlands has made large efforts to implement an Incident Management program, which was explained in the previous chapter. The procedures implemented guarantee that at least 95% of the incidents (including since debris on the road surface to big accidents) are registered on the RWS databases. Furthermore, there is other available database (ANWB) that can be also consulted to increase the accuracy of the incident registration. So it is considered that the incident database is also reliable in time and location of incidents, and do not need further checking.

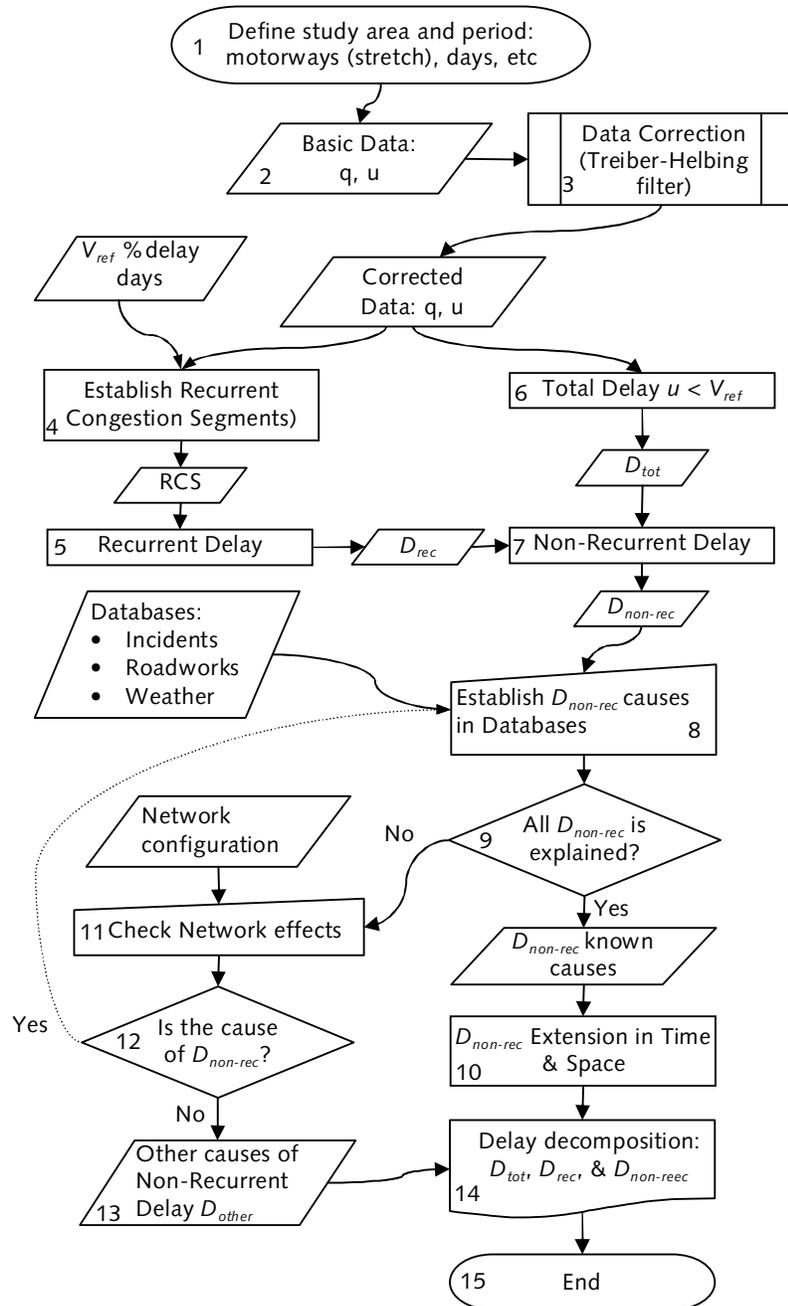
### **4.3 Assessment of Congestion**

Having all the information presented above, it is now possible to present the methodology developed to assess the different parts of congestion: total, recurrent and non-recurrent. This is the answer to research questions and objectives: how to match in time and space the information of the different data sources with congestion occurred, design a method to identify quantitatively the different parts of the congestion (and apply it to a case study, which will be carried out later on), and how is diverted the traffic flow in the network when the non-recurrent elements are present.

This methodology was built since those presented in chapter 2, taking these parts considered relevant and organizing them in a new procedure, It was also added new parts, such as considerin network effects. The general structure is based on that presented in Hallenbeck et al. (2003), including elements of Kwon et al. (2006), and Kwon & Varaiya (2005), among others, as was explained in chapter 2.

The methodology is presented in Figure 4.2 and described in the subsequent. Notice that the numbers in Figure 4.2 are the same as those that appear in the algorithm description that follows.

Figure 4.2: Methodology to assess recurrent and non-recurrent congestion



1. The first step is to define the motorway(s) stretch(es) and the period(s) to analyze. It includes information as start and end hectometer (segments  $i$ ) of the motorway (abscissas), direction(s), days, and hour (period) of the day (time  $t$ ). Since the method has been designed to deal with several motorways at the same time, this definition procedure has to include all the motorways included in the study area.

In the Netherlands road stretches or segments are defined between cross sections where detector loops are located, which is

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approximately every 500 m. This selection has to be carefully made by the user to avoid including undesirable information. For instance, if the analysis needed is only necessary for working days, in the data collection process it is necessary to exclude weekends and holidays.

2. Obtain the basic information for motorways and period under analysis, consisting of flows  $q$  and speeds  $u$ , per analysis section (hectometers between detector loops locations or segments  $i$ ) and time period (5 min aggregation time  $t$ ), for all days in the analysis period. From now on, this will be referred to as 'in space' for analysis sections  $i$  and 'in time' for time period  $t$ . All the calculations in this method are made per road section and per daytime period and only aggregated at the final step. In the case of the Netherlands, this information can be retrieved from the Monica database.
3. Check, complete if necessary, and correct the data using the process described in section 4.2.2.
4. Determine the recurrent congestion segments in time and space. First of all, it is necessary to define the congestion (delay) threshold for this study. As it was mentioned before, delay is essentially the extra time spent on traveling in a segment below a reference speed. Initially this reference speed is taken as 80 km/h<sup>7</sup>. Those stretches (in space section and time) with delays on 50% or more of the days during the study period are considered 'recurrent congestion segments' RCS.

Often, within these RCS are originated shockwaves that propagate upstream. These shockwaves are considered as fluctuations in normal traffic (cause 1 of recurrent congestion in section 2.2.1), and therefore these delays are included in recurrent congestion.

5. For all of the RCS, determine the recurrent delays  $D_{rec}$ . The delay (in vehicle hours) in segment  $i$  at time  $t$  is defined as in Kwon et al. (2006), corresponding with Equation 2.6 and Equation 2.7. This procedure is repeated for all segments  $i$  at time  $t$ , for each day in the analysis period.
6. Obtain the total delay  $D_{tot}$ , using Equation 2.6 and Equation 2.7, for all segments  $i$  at time  $t$ , for each day in the analysis period.
7. Calculate the non-recurrent delay  $D_{non-rec}$  with the formula of Kwon & Varaiya (2005), for all segments  $i$  at time  $t$ , for each day in the analysis period.

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<sup>7</sup> In Kwon et al. (2006), Kwon & Varaiya (2005), and Hallenbeck et al. methods they use a reference speed of 50 mph, which is approximately 80 Km/h.

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Equation 4.3

$$D_{non-rec} = D_{tot} - D_{rec}$$

8. Take in one hand the  $D_{non-rec}$  found in step 7 and in the other hand the information of single non-recurrent occurrences in the different input databases, described in section 4.2.1, and compare them. As it was mentioned above, this study considered three databases, but in case of having more information, this should be included here.
9. Based on the comparison made in step 8, determine for all segments  $i$  at time  $t$ , included in  $D_{non-rec}$  obtained in step 7, whether or not can be explained as a consequence of the occurrence of one (or more) non-recurrent event contained in the databases analyzed in step 8. Here is carried out the matching process of information between causes of non-recurring congestion events and resulting delays, comparing the information of non-recurrent occurrences and the outcome delays. If  $D_{non-rec}$  can be explained as a result of an (or more) occurrences within databases go to step 10, otherwise go to step 11.
10. Determine the extension in time and space of non-recurrent congestion, as appear in Kwon & Varaiya (2005) (Equation 2.10). That is, compute the  $D_{non-rec}$  obtained as a result of every occurrence considered, for all segments  $i$  at time  $t$ , for each day in the analysis period.

When segments included in  $D_{non-rec}$  extension (in time and space) overlap with RCS, determine whether or not the event brings about *extra* congestion. It means that the event may cause either greater delay intensity (i.e. lower speeds) than the recurrent congestion and/or longer congestion extension. Thus these two parts should be calculated.

The first of these two effects is greater delay intensity. The expected  $D_{rec}$  value is the average delay  $D_{mean}$  on the same road segment  $i$  at time  $t$ , considering only the days without incidents. Then, if the delay caused by the non-recurrent event is greater than this expected value, it is said that the event is causing extra delays  $D_{extra}$ . They are estimated using Equation 4.4.

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Equation 4.4

$$D_{extra} = \max(D_{rec} - D_{mean}, 0)$$

The second effect is longer extension of congestion and it may be in both time and space. For example, it could be originated in an incident that occurs within an RCS, and its effects extend further than this zone. It could be better explained in the lower part of Figure 5.13, where it is clear that there are incidents that start at RCS but its effects reached the zone outside of the RCS, and the congestion of this zone is the *extra* delay caused by non-recurrent occurrence. It is clear that the extra delays in the overlapping zone are calculated as was described above (greater delay intensity).

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In case that two or more of these occurrences are present simultaneously, apply the procedure contained in Kwon & Varaiya (2005). First look for any occurrence  $a'$  upstream of the occurrence considered  $a$ , whose duration overlaps with the duration of occurrence  $a$ . Then, the extent of incident  $a$  is limited to the distance between the locations of the two occurrences,  $a$   $a'$  Within this bound, for each time  $t$  search upstream until the speed recovers to above the reference speed to obtain the set of congested segments.

11. Verify if network effects are causing the congestion that cannot be explained as a consequence of a non-recurrent event (within the databases). Naturally, in the same manner as any traffic model, the network configuration is an input for the methodology and therefore this is necessary to be defined by the user beforehand, this process includes mainly to know the location (hectometer) of the intersections of the considered motorways. In Figure 4.2 this process is explained in the shape of the box 11, which means manual input.

In section 2.4 it was mentioned that the method used to describe network flows would be split fractions at nodes. Therefore it is necessary to check if the inflow at the node in the studied motorway is increasing as a result of a bottleneck in the neighborhood<sup>8</sup> of the node, in the other motorway. Then the effects may be either queues spilling back into the studied motorway and/or diverted inflow to the motorway link under analysis. As the methodology is designed to include several motorways, this network effects are looked for in the motorways that belongs to the study area and have intersection with the motorway under study. Naturally this process is repeated for all the motorways included in the study area.

12. If it is observed that either a greater inflow or queues spilling back originated in congestion (both recurrent and non-recurrent) exist in the links upstream connected to that one under study, then initially the  $D_{non-rec}$  cause of congestion is classified as  $D_{nt}$  'network effects'. Naturally, congestion in the upstream links is also caused by (at least) one of the sources mentioned in chapter 2, and this final cause of congestion should be identified. The dotted line in Figure 4.2 shows this; look for the final source of congestion before step 14. If there is no such flow diversion or spillback, then go to step 13.
13. In case the inflow was not appreciably higher than the expected or were not present spillback effects,  $D_{non-rec}$  cause is not included within those considered (incidents, roadworks, and weather conditions). Then the obtained non-recurrent delay is classified as 'other causes'  $D_{other}$ .

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<sup>8</sup> Recall section 2.4 where the event can be either upstream or downstream the intersection

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14. This is the final step of the algorithm, in which is assessed for all segments  $i$  at time  $t$ , for each day in the analysis period, the total delay  $D_{tot}$  and decomposed in  $D_{rec}$  and  $D_{non-rec}$ . Classify  $D_{non-rec}$  with the causes that originate them (either known or 'other'). Data is now aggregated (in time and space) for all the days and motorways in the analysis period, in order to be analyzed.

As it may be seen, this methodology has a different approach than those studied in previous chapters. All of the methods examined obtain first non-recurrent delays, then total delays and finally recurrent delays. Conversely, this proposed method first determines recurrent delays and total delays, and base on these, it computes non-recurrent delays. It is motivated in which this approach was considered a more effective way to assess all non-recurrent congestion, as it considered more reliable to characterize recurrent delay as it is present most of the time. Some of the methods reviewed in section 2.3.2 (e.g. Kwon & Varaiya, 2005) classified as a recurrent delay all the delays that cannot be explained as a result of a non-recurrent event, which would not be always the case. Furthermore, the method takes into account different causes of congestion and reckons the network effects as well as other non-determined causes of non-recurrent congestion.

In this algorithm, it is possible to introduce other causes of non-recurrent congestion easily, as long as there is information available about it. In step 8 it is possible to introduce new databases with records of other occurrences.

It has to be noticed that in the developed algorithm, two threshold values in step 4 were used. These are the percentage of days with congestion in the period analyzed and reference speed (delay threshold). In the case study, those values will be varied in order to carry out a sensitivity analysis of the impacts of them on the outcomes.

#### 4.4 Computer Tool

In order to carry out the steps mentioned in the methodology, an application tool was developed in Matlab. The general idea of this tool is to take the outputs of MoniGraph program, which are basically speeds and flows, process it together with the databases of the occurrences, to obtain the outcomes of the algorithm, just mentioned. A sketch of the computer tool with its main interfaces is presented in Figure 4.3.

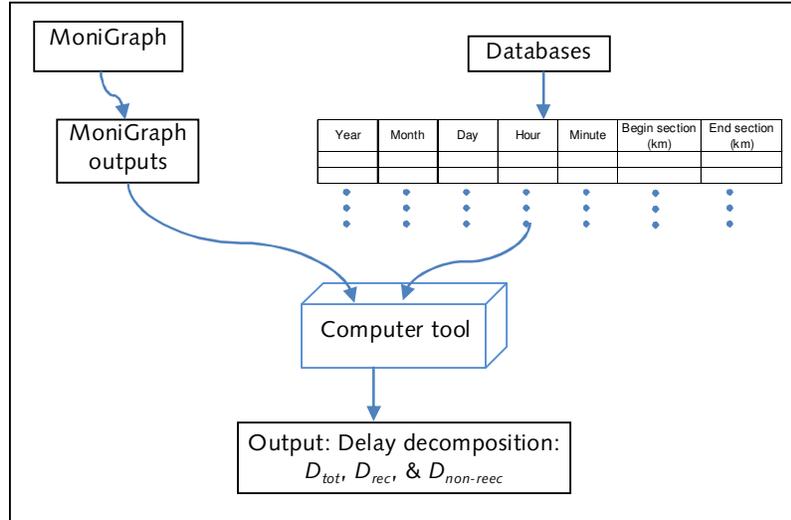
As it may be seen in Figure 4.3, the inputs required are:

- Outputs of MoniGraph for the selected motorways, in the selected period, etc.
- Databases with the occurrences. In order to be read, these databases need to be standardized. It must have seven columns with: year,

month, day, hour, and minute of the occurrence. The last two columns are the beginning and ending sections (km) of the non-recurrent causes of congestion. This considering that roadworks and weather conditions are present in road sector rather than a determined cross section.

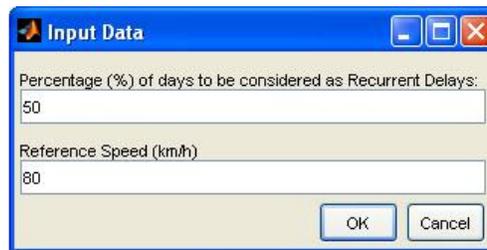
- Location of the intersections of the motorways in the study area.

Figure 4.3: Sketch interfaces computer tool.



The interface with the user displays a window asking the information required in the process. For instance, reference speed, percentage of days that will be considered recurrent delays (step 4 of the algorithm), which can be seen in Figure 4.4. The full description of the computer tool user interface is located in Appendix B. Among the regular outcomes of MoniGraph there is a file called 'BPSCComplete.mat' which contains all the information of the motorway. There is one file per day and per direction. The developed tool reads these files and captures the required information. In the final step of interface with the user, the program asks if there are intersections between the motorways found, and in that case the location (Km) of it.

Figure 4.4: Example Input window computer tool.



This tool processes the information and builds cubic (3D) matrices, in which every layer corresponds with one day of analysis. These matrices are made for speeds and flows. Then the program handles them (apply the methodology) along with the rest of the information captured, to obtain the outcomes per road per direction, as the inputs. They are also cubic matrices with (among others) total delays  $D_{totr}$ , recurrent delays  $D_{recl}$ , non-recurrent delays  $D_{non-recl}$ , non-recurrent delays caused by other causes  $D_{otherl}$ , and non-recurrent delays caused by network effects  $D_{nt}$ .

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These cubic matrices contain all the information, in which every cell corresponds to one cross section, and time period (5 min). As it was mentioned, every layer entails one day of analysis.

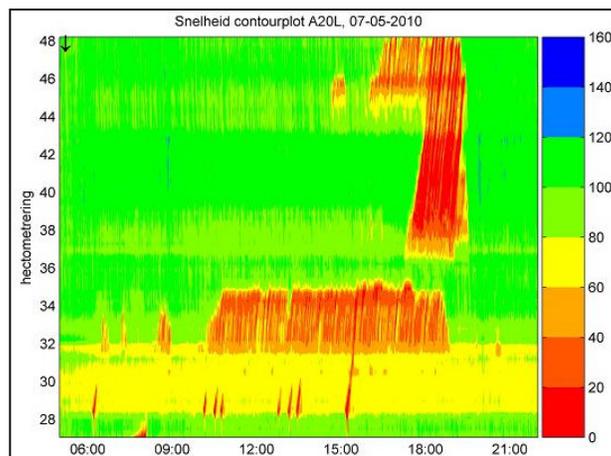
#### 4.5 Algorithm Validation

In order to corroborate that the algorithm outcomes are plausible and reproduce the conditions that were measured, it needs to be validated. To do so, it was taken data form the case study that will be presented in the next chapter. The data used were two days of the A20 motorway (one in each direction), which were selected with the highest total delay value. In these days there was recurrent delay as well as distinguishable non-recurrent delays with clear caused identified in the databases. The selected days were May 7<sup>th</sup> and 25<sup>th</sup>, for the left and right direction, respectively. Taking into consideration that speeds are inversely proportional to delays, the Monigraph output speed contour plots were used to compare them against the calculated delays, and in this way verify and validate the results obtained in with the algorithm.

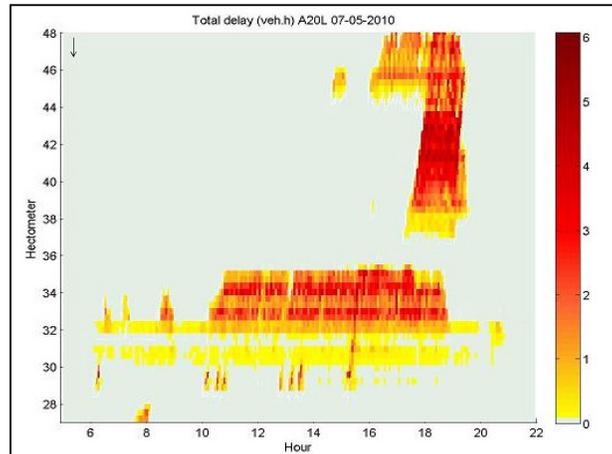
In the Monigraph speed contour plots, the color scale is shown on the right hand side and the sections (in time and space) that have speeds below 80 km/h (reference speed) are colored in yellow, orange or red, as the speed decreases. This can be seen in Figure 4.5 for the A20 left direction. On the other hand, it was drawn analogous contour plots, using delay results obtained after applying the methodology. Thus, in these two contour plot sets, delays must fit with speeds not only in location (time and space) but also in color intensities.

Figure 4.6 through Figure 4.9 present the delay contour plots for May 7<sup>th</sup>, drew with the methodology outcome delay data for the A20 left direction.

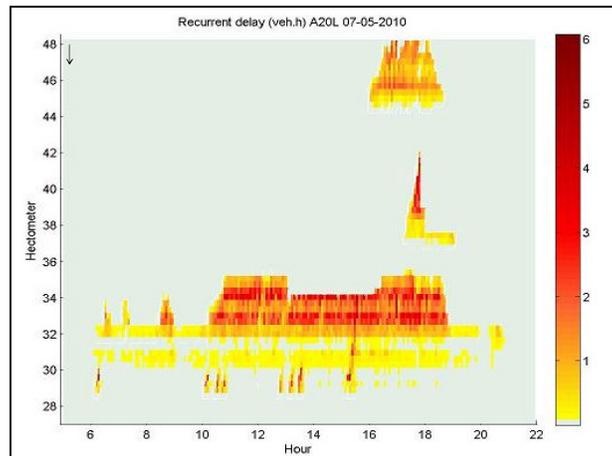
.....  
**Figure 4.5: Speed contour plot  
May 7<sup>th</sup> for the A20. Left direction**



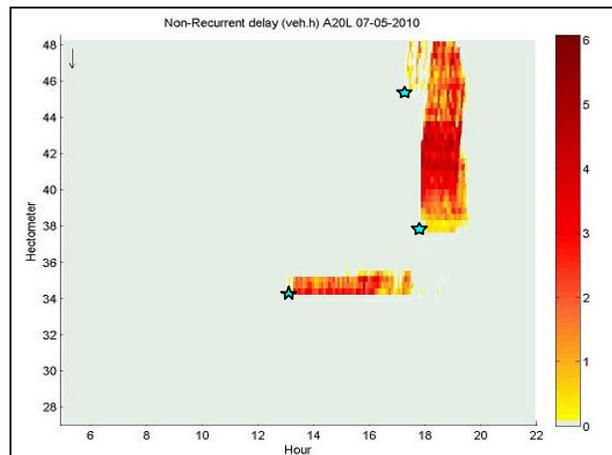
.....  
Figure 4.6: Total delay contour plot  
May 7<sup>th</sup> for the A20. Left direction



.....  
Figure 4.7: Recurrent delay contour plot  
May 7<sup>th</sup> for the A20. Left direction

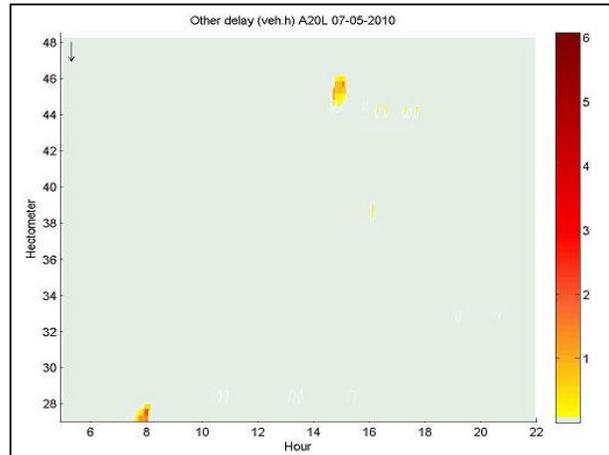


.....  
Figure 4.8: Non-Recurrent delay contour plot  
May 7<sup>th</sup> for the A20. Left direction. Stars indicate incidents locations



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.....  
Figure 4.9: Other delay contour plot  
May 7<sup>th</sup> for the A20. Left direction



When comparing Figure 4.5 with Figure 4.6, it is possible to see that the sections with speeds below 80 km/h are the same with delays, and the lower the speed, the higher the delay, as indicated by the color scales. The zone that not fully matches in these two graphs is the one between hectometers 28 and 32. In Figure 4.5 there is a yellow strip during almost the whole delay, and in Figure 4.6 this zone is smaller in time and space. This is due to the fact that speeds are exactly or just below 80 km/h, and therefore in Figure 4.6 their colors are faint. But the shockwaves in this zone shown in Figure 4.5 are also present in Figure 4.6.

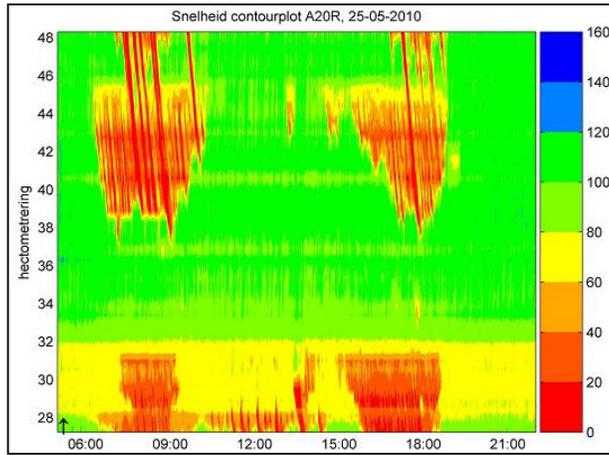
The total delays obtained were decomposed in recurrent, non-recurrent, network effects and other delays by the method described in section 4.3. They are shown in Figure 4.7 through Figure 4.9, apart from network effects, which were marginal and therefore are not shown.

Figure 4.8 presents non-recurrent delays, which in this case were all caused by incidents (as it will be explained later on in the next section) and the locations and time of these incidents are pointed out with stars. It has to be said that not all the incidents presented in May 7<sup>th</sup> are included in Figure 4.8, but only those that caused extra delays, as was explained in section 4.3. It is made clear comparing Figure 4.7 with Figure 4.8, where it can be noticed that there is an overlapping zone between hectometer 45 and 48 and 17 and 19 h. In this overlapping zone the expected recurrent delay is the one included in Figure 4.7 and the extra delay caused by the incidents is included in Figure 4.8.

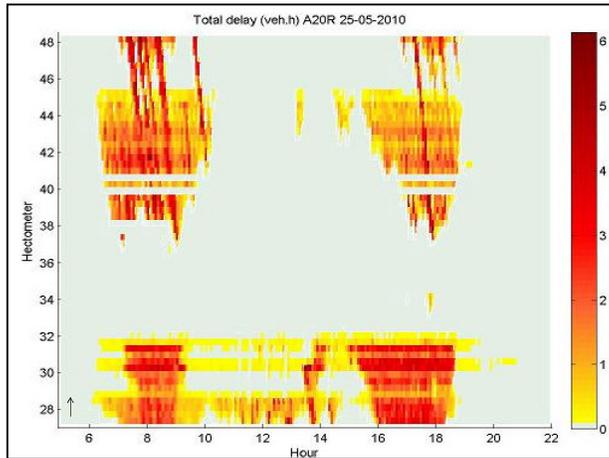
The zones that had delays in Figure 4.6, but could not be explained by the different causes of congestion (either recurrent or non-recurrent) are included in Figure 4.9. As it may be seen, they are isolated regions, where no non-recurrent occurrences were present (or at least not registered among the databases), like the one in the neighborhood of hectometer 46 at 16 h. Besides that, the zone below hectometer 28 at 8 h clearly came from outside the study area.

The delay contour plots for May 7<sup>th</sup>, drew with the methodology outcome delay data for the A20 right direction, is presented in Figure 4.10 to Figure 4.15.

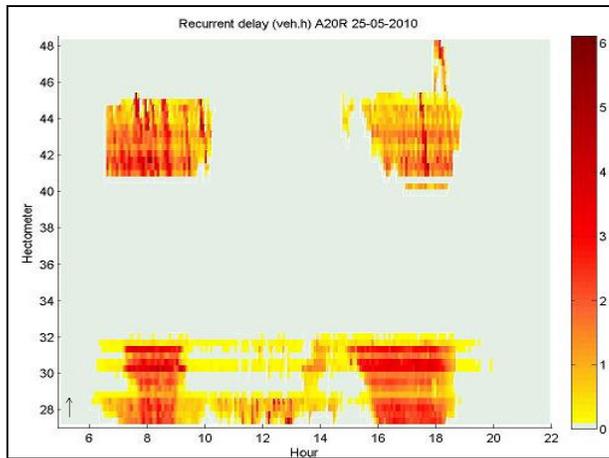
.....  
**Figure 4.10: Speed contour plot**  
May 25<sup>th</sup> for the A20. Right direction



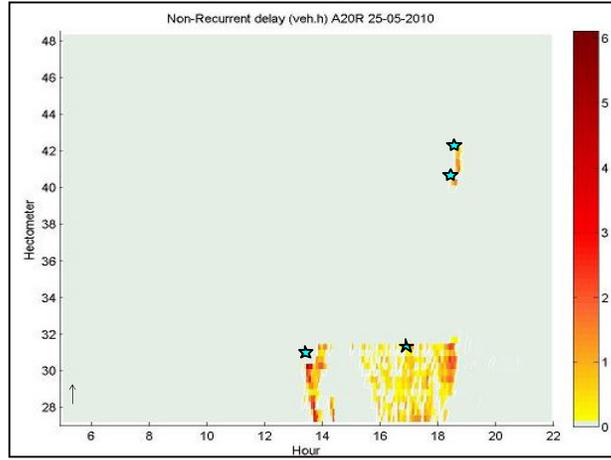
.....  
**Figure 4.11: Total delay contour plot**  
May 25<sup>th</sup> for the A20. Right direction



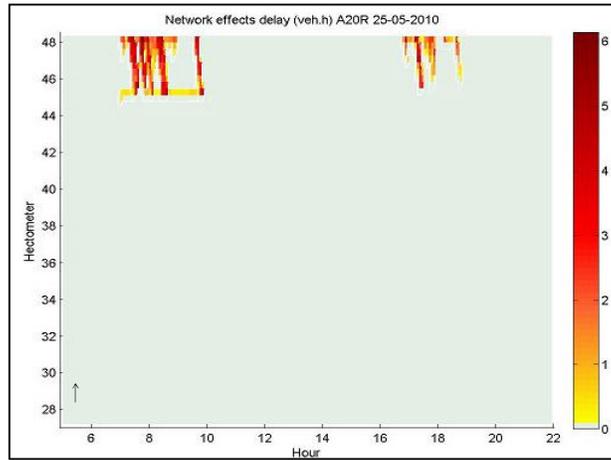
.....  
**Figure 4.12: Recurrent delay contour plot**  
May 25<sup>th</sup> for the A20. Right direction



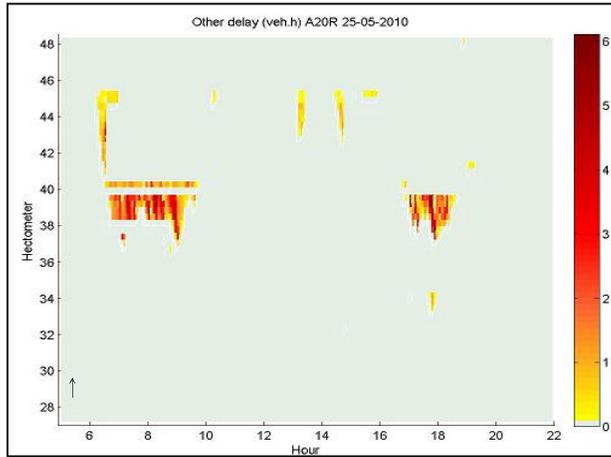
.....  
 Figure 4.13: Non-Recurrent delay contour plot May 25<sup>th</sup> for the A20. Right direction. Stars indicate incidents locations



.....  
 Figure 4.14: Network effects delay contour plot May 25<sup>th</sup> for the A20. Right direction



.....  
 Figure 4.15: Other delay contour plot May 25<sup>th</sup> for the A20. Right direction



Likewise the previous case, for the right direction it can be seen that the speed contour plot in Figure 4.10 corresponds with total delay contour plot in Figure 4.11. It has to be noticed that there are some strips in Figure 4.11 around 40 km, which may look that have no delay. They correspond with periods in which the inductor loops detectors were not working, and naturally the shockwaves and thus the delays should be continuous in these strips.

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The facts that should be noticed in this case, which were not present in the previous case, are basically two. The first is originated in the mentioned discontinuity (white strips) in the measurements of delays. They brought about that the method could not detect the extension of the recurrent congestion zone further the discontinuities (see Figure 4.11 and Figure 4.12). These zones were wrongly classified as non-recurrent delays with no recognized cause (other delays), and appear in Figure 4.15.

The second fact is that in the right direction the methodology detected and reported network effects, show in Figure 4.14. As the A20 ends up in the A12, the shockwaves observed in the figure were originated in the roadworks downstream in the A12 right direction, and they spilled back to the A20 right direction. This case was mentioned in section 2.4 and it corresponds to Figure 2.13. Thus, following the step 12 of the method of section 4.3, it was established that the final cause of these delays were roadworks, and hence they were summed up there in the overall result.

In this section it was seen that the delay results obtained applying the methodology are reliable, as they are properly reproducing field conditions. These zones (in time and location) that in the contour plots showed speeds below reference speed (80 km/h) are the same than those in the delay contour plot, drew from the methodology outcomes. Furthermore, the color intensities in both contour plots matched as well, meaning that the lower the speed the larger the delay.

For the mentioned reasons, it is demonstrated that the designed methodology works correctly and its outcomes reproduce traffic delays consistently. Thus it is suitable to use and derive conclusions from its results, and hence it will be utilized in the case study in chapter 5.

## 4.6 Conclusions

The main objective of this section was to develop the methodology to assess and to differentiate the different parts of the congestion: recurrent and non-recurrent, expressed in terms of delays. This accomplishes the first part of the research objective "Design a method to identify quantitatively the different parts of the congestion and apply it to a case study". To achieve that, first a review about the data collection process was made, followed by an outline of the databases available for the study, and the data correction process. Then the explanation of the methodology was presented, and explained the computer tool developed to automate the use of the methodology developed.

In this section, the following research questions were also solved (besides that one mentioned above): "How to match in time and space the information of the different data sources e.g. accidents (time and

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location) with congestion occurred?" in the Step 9 of the methodology developed, and "How is diverted the traffic flow in the network when the non-recurrent elements are present?", in step 11.

As a result of the above mentioned the methodology for separating recurrent and non-recurrent congestion was developed and explained, which is one of the core aspects of this study. This methodology covers the gaps noticed in the existing methodologies: it handles various causes of non-recurrent congestion, makes possible to include other causes, includes the evaluation of network effects, is a structured method, and accurately assesses all the delay components.

It has to be mentioned that originally one of the main research objectives was to develop the methodology showed in this chapter. Nonetheless among the original objectives it was not included to develop a computer tool, and therefore this is an extra achievement in the process.

In the last part of the chapter the methodology was applied to a situation with real data, to corroborate that it works properly. In this process it was found that the delay results obtained applying the methodology are reliable, as they properly reproduce field conditions. These motorway sections that in the contour plots showed speeds below reference speed (80 km/h) in certain time periods of the day are the same than those in the delay contour plot, drew from the methodology outcomes. Furthermore, the color intensities in both contour plots matched as well, meaning that the lower the speed the larger the delay. Hence, it was validated the designed methodology, as it works correctly and its outcomes reproduce traffic delays consistently. Thus the methodology is appropriate to be utilized in the case study in chapter 5, in which real data will be used, in order to obtain results and analyze them.

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## 5. Case Study

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In the general structure of the report, after the literature review, the policies review, and having developed the methodology to assess non-recurrent delays, the next step involves to apply the methodology to a case study. It takes real data retrieved from the described databases to evaluate the performance of the methodology and to derive results and conclusions. The results obtained in this chapter are the base for the next two chapters, which are policy recommendations and the final chapter with conclusions and recommendations.

The first section of the chapter describes the area selected for the case study, with the motorways included there, and the time framework of the study. In section 2 of the chapter some reflections are made about the actual use of the databases in the case study. In section 3 the outcomes of the methodology are tested using data from the case study, to verify if it is working properly. Section 4 shows and analyzes the delay results derived from the case study. Since in the methodology described in the previous chapter some threshold values are included, in section 5 of the chapter they are changed with the aim to make a sensitivity analysis of the results to these values. In the last part of the chapter its conclusion are included, as usual.

This chapter assesses and decomposes delays in the motorways in the study area, caused by non-recurring events such as roadworks, incidents, adverse weather conditions, and network effects. This gives the response to the main research objective, along with computing the percentage of the total delays that is produced by non-recurrent causes (research question 4), and what is causing the biggest share of non-recurrent congestion (research question 5).

### 5.1 Setup Case Study

As was mentioned before, the methodology needs to be proven in a case study with real data. As one might expect, the case study is chosen within the Netherlands, taking motorways that belong to the main road network. In the scope of the study it was decided to include the Randstad area, which is the busiest part of the country and presents the highest levels of congestion. It was the first selection criterion for the study area. The next was to choose a closed network in which it is possible to clearly observe and assess the network effects mentioned throughout the report. There are various parts of the network in the Randstad area that fulfill these two criteria. Then it was intended to include as much as possible interurban motorways or at least that has the least possible effect of urban areas. For instance the ring roads in Amsterdam and Rotterdam do not fulfill this criterion. Considering the

size of the remaining possibilities, it was chosen the case study describe in the subsequent.

The selected motorways were A4, A13, A20, and A12, which are presented in Figure 5.1. They have a triangle-shaped configuration. Although it has a part in the Rotterdam area, it is not the majority of the zone studied. As it may be noticed in Figure 5.1, the A16 may have an effect on the A20 as it intersects the last in the study area and therefore it was decided to be included as well. Then, in the north-west border of the study area is The Hague, in the south boundary is Rotterdam, and the eastern edge is Gouda. Zoetermeer and Delft are also within the captive area. The motorway stretches (km) included in the study as well as their location, are listed in Table 5.1.

Figure 5.1: Case study Zone: A4, A13, A20, A12, and A16 in the Netherlands (Google maps)



Table 5.1: Road sections and geographical location of the motorways in the study area

| Motorway | Begin section (km) | Location  | End Section (km) | Location  |
|----------|--------------------|-----------|------------------|-----------|
| A4       | 44.4               | The Hague | 57.0             | Delft     |
| A12      | 5.5                | The Hague | 34.0             | Gouda     |
| A13      | 3.5                | The Hague | 19.5             | Rotterdam |
| A16      | 15.5               | Rotterdam | 18.0             | Rotterdam |
| A20      | 27.0               | Rotterdam | 48.5             | Gouda     |

In the study both directions were included. In the Netherlands the directions are distinguished as Left and Right. To differentiate them, the convention establishes that the motorway must be taken in the direction in which the motorway increases the abscissas (Km). For example the A12, as it may be seen in Table 5.1 kilometers grow from The Hague to Gouda, thus the Right direction is this one and the left lane is the one Gouda – The Hague.

The time period selected included the month of May in 2010, taking working days. As it is well known, flows in weekends are different than during weekdays, for this reason the last were not included.

Clearly, the case study must include roadworks, as it is one of the main matters in this study. According to WPK database, there were permanent roadworks located in the A12 motorway right direction,

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between road sections 29.9 and 32.7 km. In this motorway stretch noise barriers were built between March 8<sup>th</sup> and June 4<sup>th</sup>. The information in WPK database indicates that capacity was reduced to approximately 90% of its original value.

## 5.2 Databases

The actual dataset that was included in this study intended to cover whole weeks, rather than the month itself. Therefore, in a more accurate sense, the actual data comprised between 3<sup>rd</sup> and 30<sup>th</sup> of May. Taking into consideration that there were some holidays in the month, then the 5<sup>th</sup>, 13<sup>th</sup>, and 24<sup>th</sup> were also ruled out of the analysis. During the process of retrieving data, it was not possible to capture data from Monica database for the 4<sup>th</sup>, 6<sup>th</sup>, 20<sup>th</sup>, and 26<sup>th</sup> of the month, for all of the motorways studied. It is not clear the reason for this structural failure in the recovering process in the database.

As it was mentioned in section 4.2.1, the weather database has to be built for the case study. It was also mentioned there that the result of this process was rain intensity per road section (in time and space) for each motorway in the case study. These values of rain intensity were correlated with those threshold values that appear in Jonkers, et al. (2008). This is a survey made in the Netherlands to implement dynamic speed limits under rainy conditions. They say that between 2.5 and 6 mm/h it is still possible to drive at 100 Km/h, but if the rain intensity is higher than 6 mm/h, the speed limit should be dropped to 80 Km/h. Consequently it was decided to take these values, and filter out the locations and time where the rain intensity were higher than 6 mm/h (where the flow begin to be hindered by the rain) to be included as the weather database to compute non-recurrent causes of congestion.

This fact that the weather database as such is still not available as the other databases, hinders the process of computing non-recurring delays. Besides that, this database includes only rain and there are other sources that need to be included in the future such as snow or fog.

## 5.3 Results

The fifteen steps methodology was applied to the case study described above, using the tool developed in Matlab, described in the previous chapter.

The algorithm first calculates recurrent congestion and in this section this is the first result presented. The next part explores total delays and non-recurrent delays. The outcomes of the case study include the results obtained for all motorways in the study area, with one result set for each direction. Hence, there are 10 sets of quantities (speed, volume, delays, et cetera) available, assessed or calculated during the process. Nonetheless, this is considered an excessive amount of data to be presented in this report. Therefore, it was decided to select some

motorways to be presented. The selection criteria were the largest amount of non-recurrent occurrences, and the highest levels of congestion, since in those cases it is possible to see more clear the way in which the proposed methodology works. The A12, where the roadworks in the study area are carried out, is also included, even though it did not present the highest delays. Based on these criteria, the selected motorways were the A12, A13 and the A20. The result set for the remaining motorways (A4 and A16) are included in the Appendix A.

Taking the mentioned facts into consideration, the results for the A12, A13 and A20 will be presented per direction. The first result will be the speed contour plot, since graphically is easier to understand the different outcomes of the methodology. First it was determined a reference day, which will be used as a comparison base. For all the motorways it was analyzed the total delay results. These values were aggregated per day, and then they were averaged over the analysis period, per motorway. It was observed that the total delay obtained in May 3<sup>rd</sup> was the closest to the average value in most of the cases. Thus the 3<sup>rd</sup> of May is selected as base day since it is the closest to the average conditions. It is compared against another day, which is either the day with the highest non-recurrent congestion or the largest number of non-recurrent events, among the days in the study period.

This is followed by the analysis of the delay obtained, with the diverse elements in which it was decomposed. The following part concentrates on incident analysis attempting to characterize them in terms of means and standard deviations. Finally, the network effects are studied trying to observe their amount and the impacts on the different motorways.

The last part of this section presents the summary of the results obtained for all the roads considered within the study area. It goes without saying that they are not as detailed as the ones presented for the A12, A13 and A20. The objective is to present the results aggregated for the period studied.

### 5.3.1 Recurrent Congestion Location

The first outcomes resulting from the algorithm are those road sections that used to have congestion during the analysis period, on 50% or more days. Those sections are listed in Table 5.2, which presents the location (km) and time of the beginning and end of the road stretch, this per road and per direction.

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**Table 5.2: Motorway sections with recurrent congestion in time and space**

| Motorway | Direction | Section From (Km) | Section To (Km) | Period begin | Period end |
|----------|-----------|-------------------|-----------------|--------------|------------|
| A12      | L         | 5.5               | 5.8             | 5:00         | 21:55      |
|          |           | 6.3               | 6.9             | 7:50         | 8:50       |
|          |           | 15.0              | 15.4            | 7:50         | 8:30       |
|          |           | 28.0              | 28.3            | 17:05        | 17:45      |

| Motorway | Direction | Section From (Km) | Section To (Km) | Period begin | Period end |
|----------|-----------|-------------------|-----------------|--------------|------------|
| A12      | R         | 5.6               | 6.0             | 5:00         | 21:55      |
|          |           | 33.7              | 34.3            | 8:05         | 8:25       |
|          |           | 33.7              | 34.3            | 15:45        | 18:50      |
|          |           | 7.9               | 9.4             | 17:10        | 17:45      |
| A13      | L         | 17.0              | 19.5            | 5:00         | 21:55      |
|          |           | 9.0               | 10.0            | 17:15        | 17:40      |
|          |           | 11.5              | 12.1            | 18:00        | 18:40      |
| A13      | R         | 17.0              | 19.1            | 5:00         | 21:55      |
|          |           | 10.5              | 13.2            | 7:20         | 8:40       |
|          |           | 5.5               | 7.5             | 7:35         | 8:50       |
|          |           | 15.5              | 16.5            | 7:25         | 8:45       |
|          |           | 19.1              | 19.7            | 10:45        | 13:15      |
|          |           | 16.5              | 17.0            | 13:25        | 13:40      |
| A16      | L         | 5.5               | 16.5            | 14:35        | 19:00      |
|          |           | 15.7              | 17.7            | 6:30         | 8:40       |
| A16      | R         | 15.7              | 17.7            | 16:55        | 18:15      |
|          |           | 15.7              | 17.0            | 16:00        | 17:55      |
| A20      | L         | 28.4              | 32.0            | 5:00         | 21:55      |
|          |           | 32.0              | 35.0            | 6:15         | 9:55       |
|          |           | 32.0              | 33.2            | 12:30        | 13:55      |
|          |           | 44.4              | 48.2            | 15:50        | 18:35      |
|          |           | 32.0              | 34.7            | 15:55        | 18:45      |
| A20      | R         | 36.6              | 38.3            | 17:15        | 17:55      |
|          |           | 28.1              | 31.9            | 5:00         | 21:55      |
|          |           | 27.2              | 27.8            | 6:00         | 20:05      |
|          |           | 43.0              | 44.9            | 6:50         | 7:55       |
|          |           | 40.6              | 45.3            | 15:40        | 18:40      |

The first thing noticed on Table 5.2 is that the A4 (both directions) is not included. It is also noticeable that there are road stretches (especially in the A13 and A20) that show recurrent delays the whole day (i.e. speeds are lower than reference speed of 80 km/h). For instance look the A13 in both directions between kilometers 17.0 and 19.5. This is at the zone of the end of the road and the junction with the A20, which may explain that speeds in this stretch are lower than the reference speed. Thus in this zone there is a physical bottleneck producing recurrent congestion, which is the cause number 3 of recurrent congestion indicated in section 2.2.1. This zone tends to present severe congestion, which spillbacks.

Again, the A20 and the A13 showed a complex behavior with zones of recurrent delays close to each other in time and space. For instance the A20 Left direction between Km 32 and 35, presents recurrent congestion between 6:15 h and 9:55 h, and then again in (approximately) the same sections between 12:30 and 13:55 h. This section is adjacent to that just described, and it uses to present congestion as a result of spillback effects.

These results are part of the outcomes of the proposed method, which to a certain extent are additional benefits. The developed method can detect and assess congestion present most of the time, providing hard data that could have an application in other fields (e.g. detection of the critical spots in the network).

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### 5.3.2 Motorways Analysis

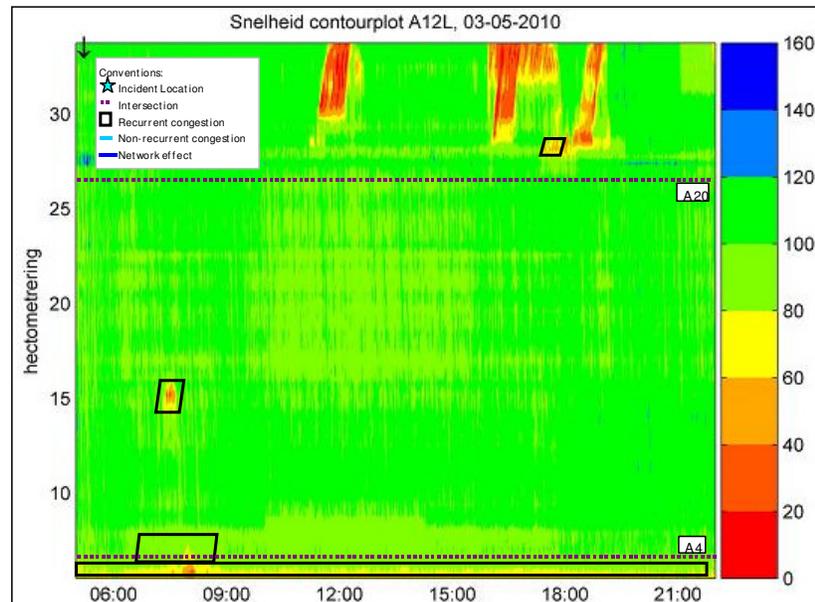
This part of the section presents an overview of the results obtained for three of the roads inspected: the A12, A13 and the A20, per direction. This section will follow the order established above.

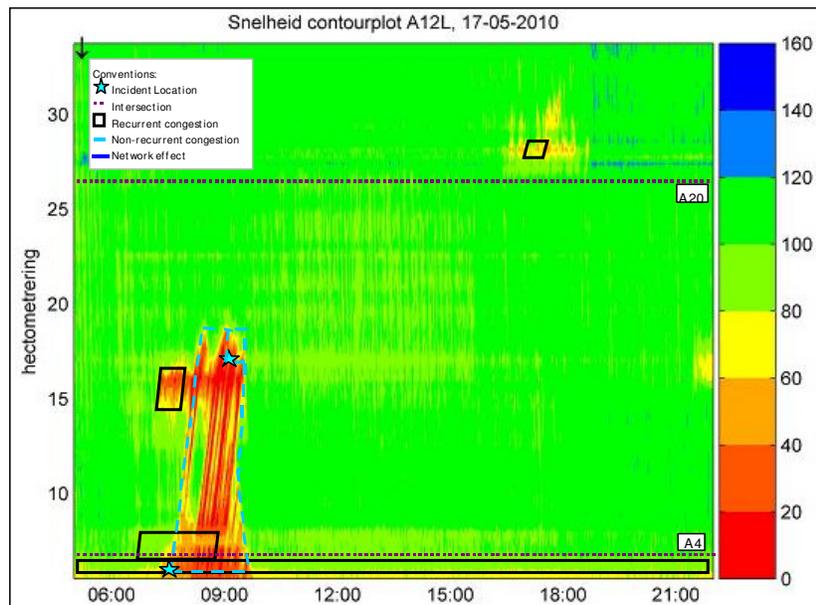
#### 5.3.2.1. A12 Results

The first motorway analyzed was the A12. This motorway presented all the non-recurrent causes of congestion, including roadworks in the right direction.

Figure 5.2 shows the speed contour plots for the A12 left direction (Gouda – The Hague), for the reference day (May 3<sup>rd</sup>) and comparing day (May 17<sup>th</sup>), with the different congestion zones found by the algorithm. The arrow in the upper left part of the figures indicates direction of the flow. As it is mentioned in the conventions, this figure includes location of incidents, location of the intersection with other motorways, sections with recurrent congestion non-recurrent congestion, and network effects. It has to be mentioned that sections with recurrent congestion includes those sections listed in Table 5.2 as well as shockwaves originated within them, corresponding with step 4 of the algorithm. Figure 5.2 corroborates the information presented in Table 5.2, the recurrent congestion zones in the A12 are small, compared to these of the A13 and the A20. These zones of recurrent congestion can be found in the morning and evening peak hours.

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Figure 5.2: Speed contour plots for the A12 Left direction (Gouda – The Hague). Base day (up) and comparing day (down).



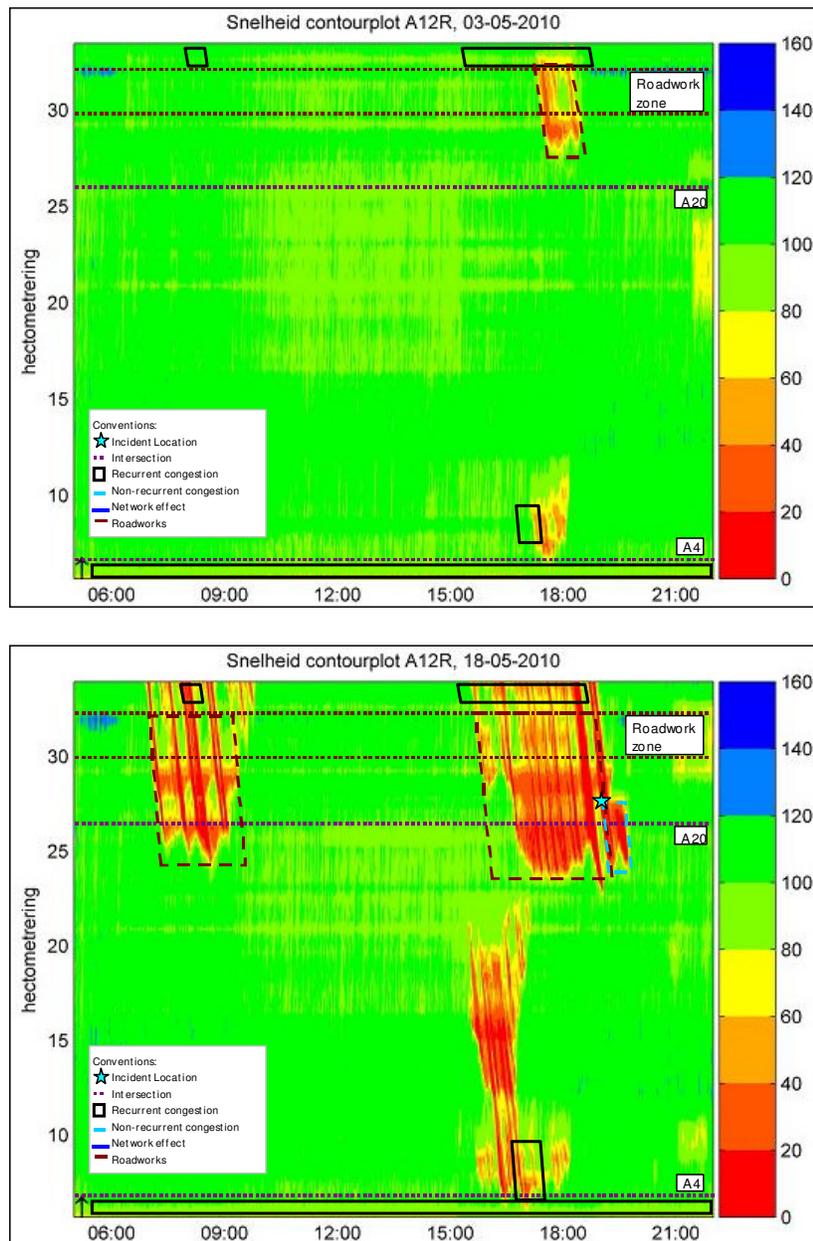


On May 3<sup>rd</sup> there were no incidents that produced extra delays and it is clear that there are several zones of non-recurrent delays that could not be explained as a result of non-recurrent events. On the contrary on May 17<sup>th</sup> (lower part of Figure 5.2) there were two incidents, and it is interesting to note that their effects overlap. The first took place at 8:07 h at 5.8 km section and in the figure it is possible to see that their effect overlapped with the second, that happened at 9:13 h at 19.2 Km section. Both resulting congestions are surrounded by the blue dashed-lines. The way to deal up with this event is found in step 10 of the algorithm: the extent of the first incident  $a$  is limited to the distance between the locations of the two occurrences. Therefore, the first incident resulted in a (extra non-recurrent) delay of 1119 veh.h and 4 veh.h for the second. This result is clear looking the lower part of Figure 5.2.

The results for the right direction (The Hague - Gouda) are presented in Figure 5.3. The base day is May 3<sup>rd</sup> and it was compared against May 18<sup>th</sup>. As it was mentioned above, on the A12 there were permanent roadworks carried out during the study period, amid hectometers 29.9 and 32.2. This zone is marked in Figure 5.3 with the brown dotted line, and the sign in the middle. In the figures below is clear the bottleneck formed in the zone where the roadworks begins. After the roadwork zone there is zone of recurrent congestion in the evening peak (between 15:45 and 18:50 h), which mainly consists of shockwaves originated downstream further the study area.

In the lower part of Figure 5.3 it is possible to distinguish several zones of delays that do not lay within the mentioned zones, and therefore are classified as  $D_{other}$ . For instance, for the bottleneck observed approximately at hectometer 20 in the evening (around 15:30 and 17:00 h), a cause cannot be found in the databases studied.

Figure 5.3: Speed contour plots for the A12 Right direction (The Hague - Gouda). Reference day (up) and comparing day (down).



Regarding the analysis of total delays  $D_{total}$  for the AM, MID and PM periods for left and right direction are shown in Figure 5.4. As it was expected, the delays obtained for the right direction were larger than these for the left direction, taking into consideration the roadworks. In the figures above it was noticed that in general, most of the delays were present in the AM period for the left direction, and in the PM period for the right direction.

The total delays  $D_{tot}$  obtained for the whole day were decomposed in  $D_{nonrec}$  and  $D_{other}$  for the A12 in the analysis period, as is presented in Figure 5.5.

Figure 5.4: Total delay A12. Left and Right direction per period of the day

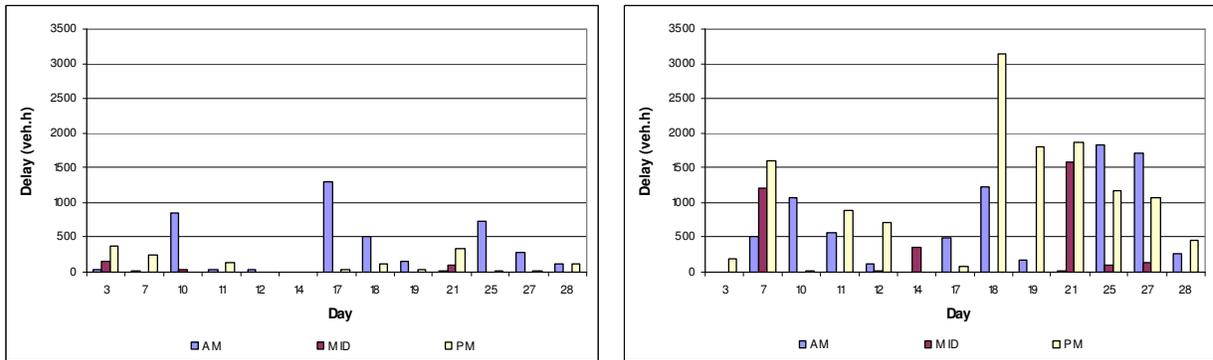
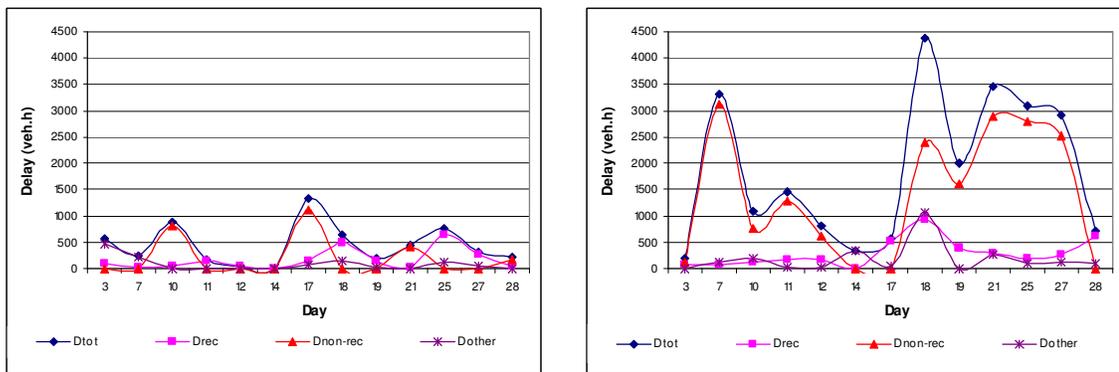


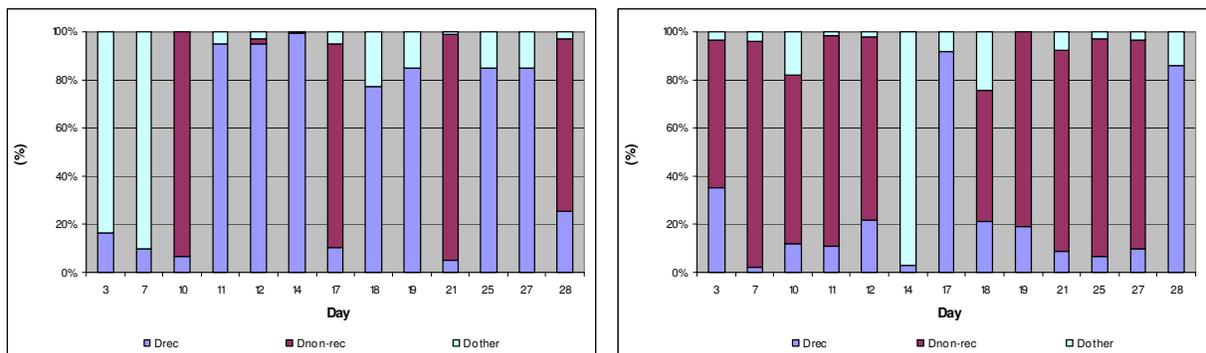
Figure 5.5: Delay decomposition for the A12. Left and Right direction



The figures above show that  $D_{nonrec}$  conducted  $D_{tot}$  in both directions. Naturally the effect is greater in the right direction, due to the roadworks, as is explained later on. It can be seen that the delay results obtained for the right direction is about three times the results for the left direction,

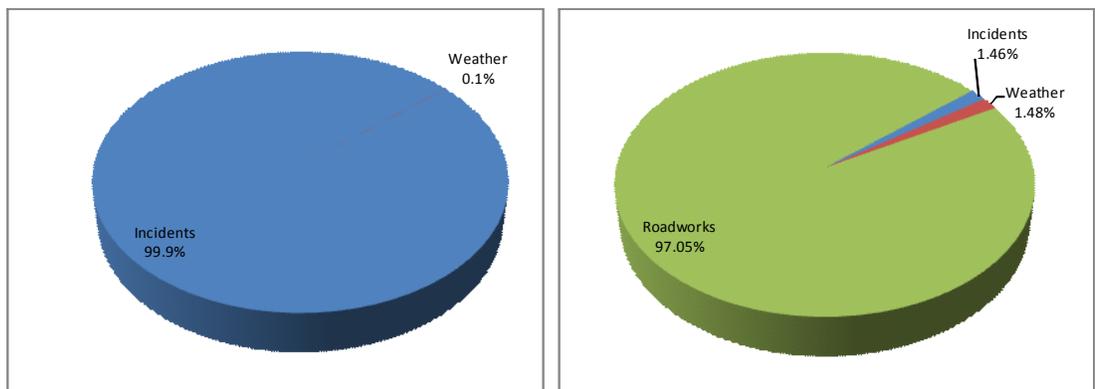
The share of the total components mentioned in  $D_{tot}$  is presented in Figure 5.6. As it was shown in Figure 5.5, this figure shows that the share of  $D_{nonrec}$  is the largest, especially for the right direction. It has to take into account that although this is the only motorway that had roadworks in the analysis period, the other two causes of non-recurrent congestion (incidents and weather conditions) were also present. As was explained in Figure 5.2, most of the delays obtained the May 3<sup>rd</sup> for the left direction were classified as  $D_{other}$ .

Figure 5.6: Share of different factors in total Delays for the A12. Left and Right direction



The non-recurrent sources of congestion detected on the A12 that caused extra delays during the analysis period were roadworks (only in right direction), incidents and adverse weather conditions. The last implies that the rain intensity was higher than 6 mm/h. It was measured on the evening of the 12<sup>th</sup> of May in the vicinity of the hectometers 6, 9, and between 24 and 28. Naturally it was present in both directions of the road. The percentage of  $D_{nonrec}$  value of the mentioned causes of non-recurrent congestion is shown in Figure 5.7.

Figure 5.7: Percentage of non-recurrent causes of congestion in  $D_{nonrec}$  value for the A12. Left and Right direction



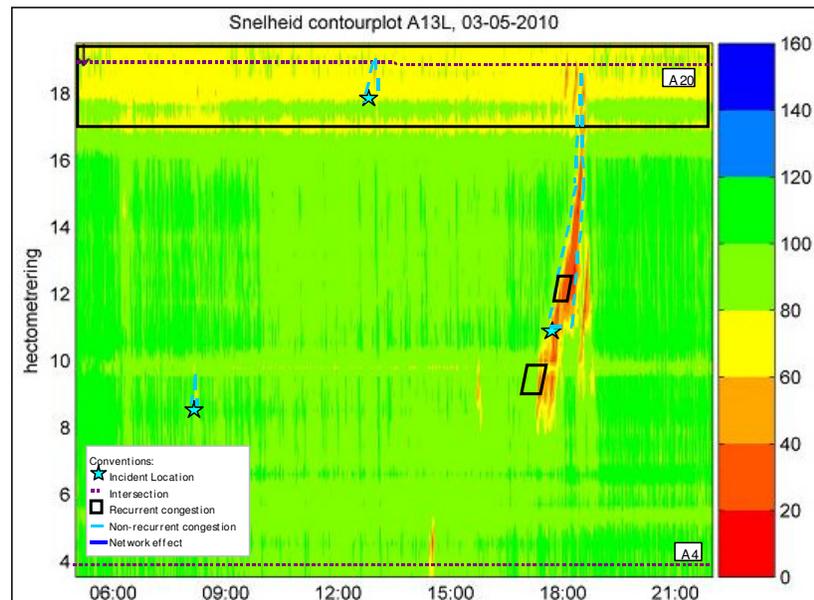
Based on the information presented in the figures above, it was concluded that adverse weather conditions had a marginal contribution (less than 1%) in delays in the case study. In the left direction delays were caused by incidents whereas in the right direction delays were caused by roadworks.

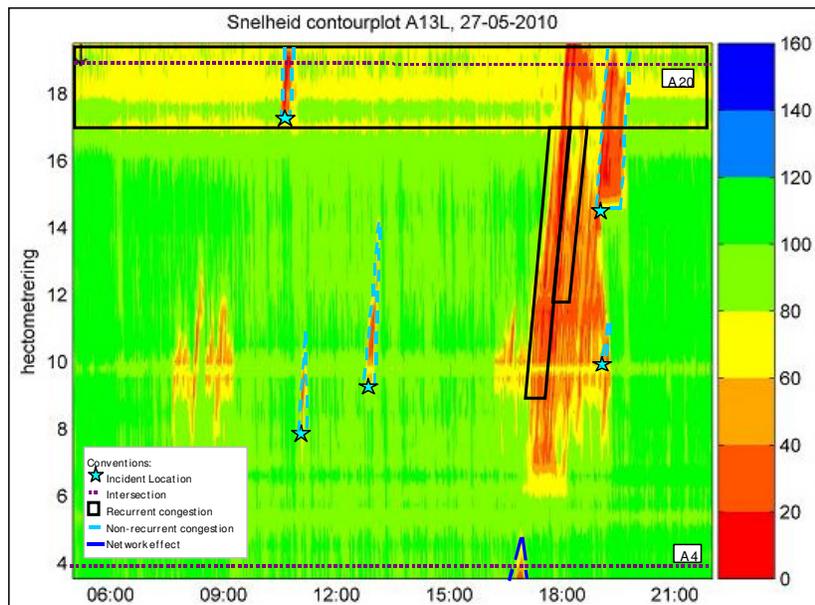
### 5.3.2.2. A13 Results

The speed contour plots for the left direction (The Hague - Rotterdam) are presented in Figure 5.8. Similarly to the A12 case study, the arrow in the upper left part of the figures indicates direction of the flow, the conventions indicates the meaning of the different symbols used in the figure, and the recurrent congestion zones include RCS as well as shockwaves originated within them. The reference day is compared with the day in which was obtained the highest value of non-recurrent delays, May 27<sup>th</sup>.

In the upper contour plot there were three incidents, the second happened at 12:53 h at section 18.2, and it caused minor extra delays (above the average for these sections, as explained in section 4.3), shown in Figure 5.8 by the dashed line zone. In the case of the incident that occurs at 17:56 h, 11.1 Km, its effects were felt beyond the recurrent congestion zone and therefore the algorithm detects and assesses it, which corresponds with the zone surrounded by the dashed blue line. It is also the case for the 27<sup>th</sup> of May, where it is clear that there are incidents that cause non-recurrent delays presented as the dashed-line zones. Notice the incident occurred in hectometer 14.6 at 18:44 h that produced extra delays in both extension and intensity in the zone of recurrent congestion.

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Figure 5.8: Speed contour plots for the A13 Left direction (The Hague – Rotterdam). Reference day (up) and comparing day (down).





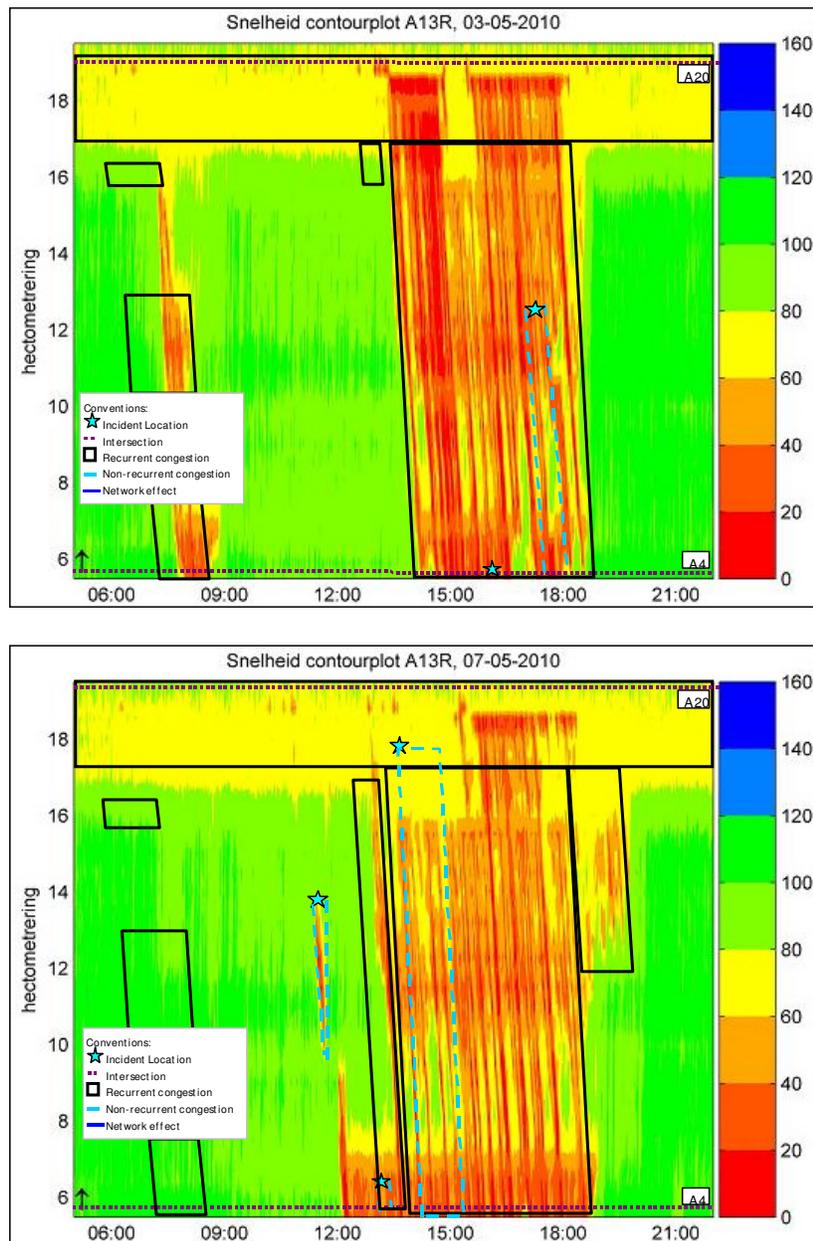
Moreover, on the 27<sup>th</sup> can be appreciated some network effects, the zone in the dark blue dashed line, coming from the A4. Finally, these zones that are not content within any of the mentioned zones, correspond with other delays  $D_{other}$ . It is clear that approximately on kilometer 6 at 17 h there is a bottleneck that spilled back for several kilometers (at least 10) and lasted about 2 hours. However there was no information about non-recurrent causes of congestion in the databases used and for that reason the algorithm cannot detect them and they were reported as  $D_{other}$ .

The same exercise was made for the right direction (Rotterdam - The Hague), which is presented on Figure 5.9. The Reference day is May the 3<sup>rd</sup> and it was compared against the 7<sup>th</sup>.

In the Figures above it can be seen that the recurrent congestion zones are much bigger than those for the Left direction. Here can be noticed that non-recurrent locations correspond with the peak periods: between 7:00 and 9:00 h, and in the evening between 14:30 and 19:00h, which is longer than expected.

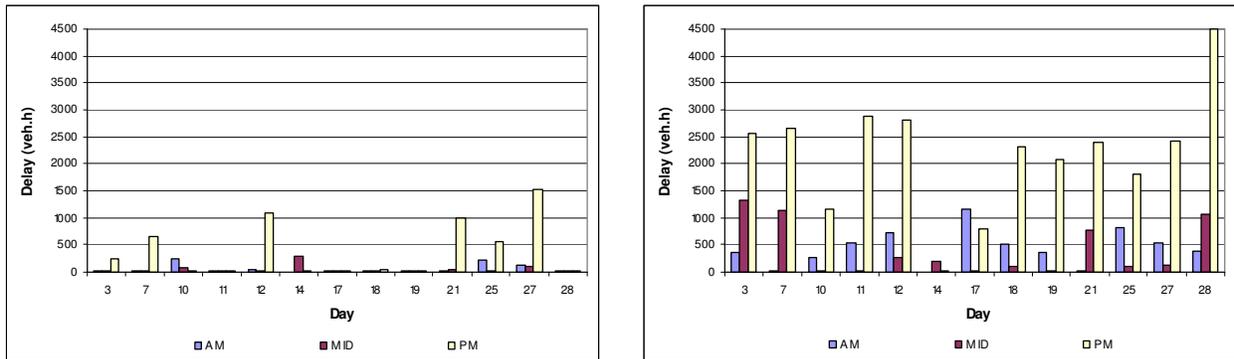
Likewise for the left direction, here are indicated the delays reported as  $D_{nonrec}$  for the incidents occurred, being clear the relationship between incident – and output delay. For the 7<sup>th</sup> of May case, the zones classified as  $D_{other}$  other delays correspond mainly with a bottleneck located near the hectometer 7 between 12:00 and 19:00 h, which once more had no an identified cause.

Figure 5.9: Speed contour plots for the A13 Right direction (Rotterdam – The Hague). Reference day (up) and comparing day (down).



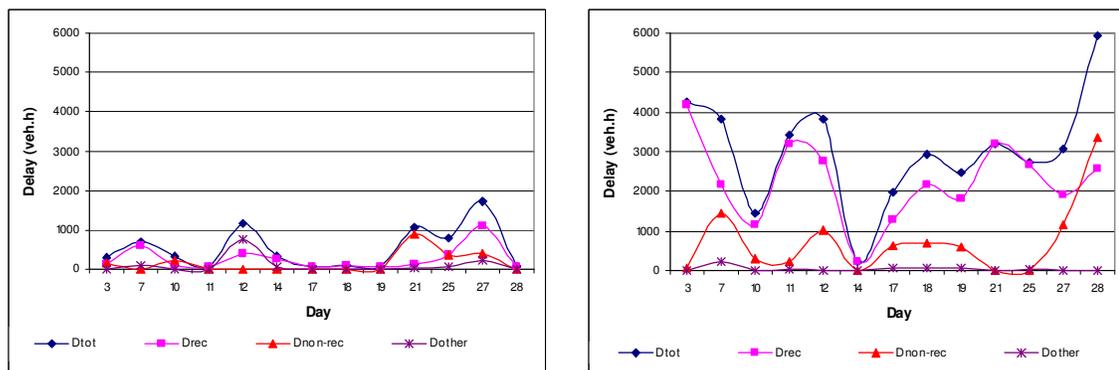
On the topic of total delays, the results obtained for AM, MID, and PM periods of the day, for both directions are presented in Figure 5.10. There can be seen that most of the delays were present during the PM period, for both directions, which is not the expected result. Usually one direction presents the biggest delays in AM period and the other direction during PM period. The values of total delay  $D_{total}$  determined for the right direction were bigger than those for the left direction as the first are typically around 2500 veh.h while in the second highest delay values are around 1000 veh.h.

Figure 5.10: Total delay A13. Left and Right direction per period of the day



The behavior of the total delay  $D_{totr}$  and its different components  $D_{recr}$ ,  $D_{nonrecr}$  and  $D_{other}$  for the A13 (whole days) for the period analyzed, is shown in Figure 5.11.

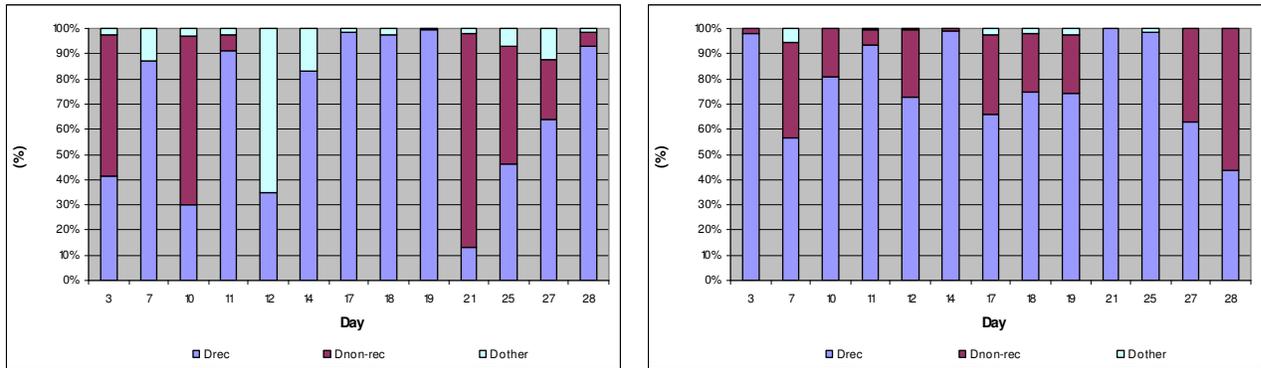
Figure 5.11: Delay decomposition for the A13. Left and Right direction



In the previous figures can be seen that for right direction, total delays are mainly due to recurrent delays, whereas in left direction the share of the different components are more spread. More accurately, the contribution of each factor in the total delay, per day of the analysis period is presented in Figure 5.12. this figure

Figure 5.12 confirms that for most of the days the biggest share of the delays is recurrent, especially for right direction. However there are days in which the other sources of congestion contribute more in total delays. For instance, in the 12<sup>th</sup> (left direction),  $D_{other}$  had the biggest portion on  $D_{total}$ .

Figure 5.12: Share of different factors in total Delays for the A13. Left and Right direction



In the A13 the rain intensity detected were below the threshold value of 6 mm/h, and therefore it was not included in the database of non-recurrent causes of congestion. Additionally was also mentioned that roadworks in the period analyzed were present only in the A12. Hence the only cause of non-recurrent congestion found in the A13 was incidents. The results obtained from them per direction, are registered in Table 5.3. There can be found the total number of incident registered, total (sum) extra vehicle hours obtained from them, together with the average, and the standard deviation.

Table 5.3: Incident analysis per direction for the A13

|                          | Left Direction | Right Direction |
|--------------------------|----------------|-----------------|
| Number of Incidents      | 17             | 31              |
| $D_{nonrec}$ Sum (Veh.h) | 1040.9         | 9473.3          |
| Delay average (Veh.h)    | 61.2           | 305.6           |
| Delay Standard deviation | 105.5          | 393.8           |

As may be noticed, average values of extra delays caused by incidents are lower than standard deviation. It denotes that the values are spread, with variations that include different orders of magnitude (from 0.05 to > 500 veh.h).

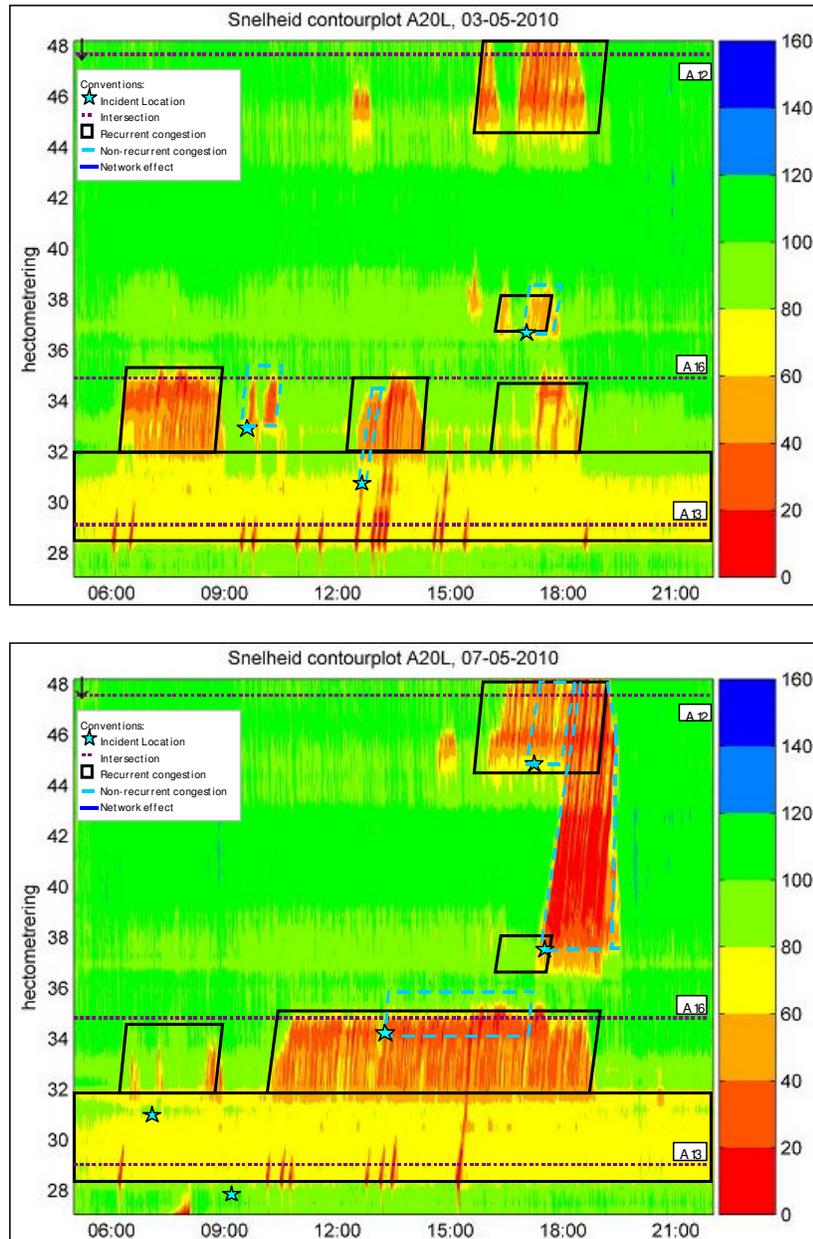
The results obtained for  $D_{nt}$  showed that these effects were insignificant for the right direction and for the left direction they were concentrated on a few days. Naturally this effect can be felt on these days in which the motorways that the A13 has intersections in the area under study presented the highest delays, for example on May 21<sup>st</sup> PM period (with 451.0 veh.h that is considered significant comparing with the rest of the values), which matches with the A4 biggest delays.

### 5.3.2.3. A20 Results

The next motorway examined was the A20. The resulting contour plots for the left direction (Gouda - Rotterdam) for the reference day (May 3<sup>rd</sup>) and comparing day (May 7<sup>th</sup>), are presented in Figure 5.13. The

arrow in the upper left part of the figures indicates direction of the flow.

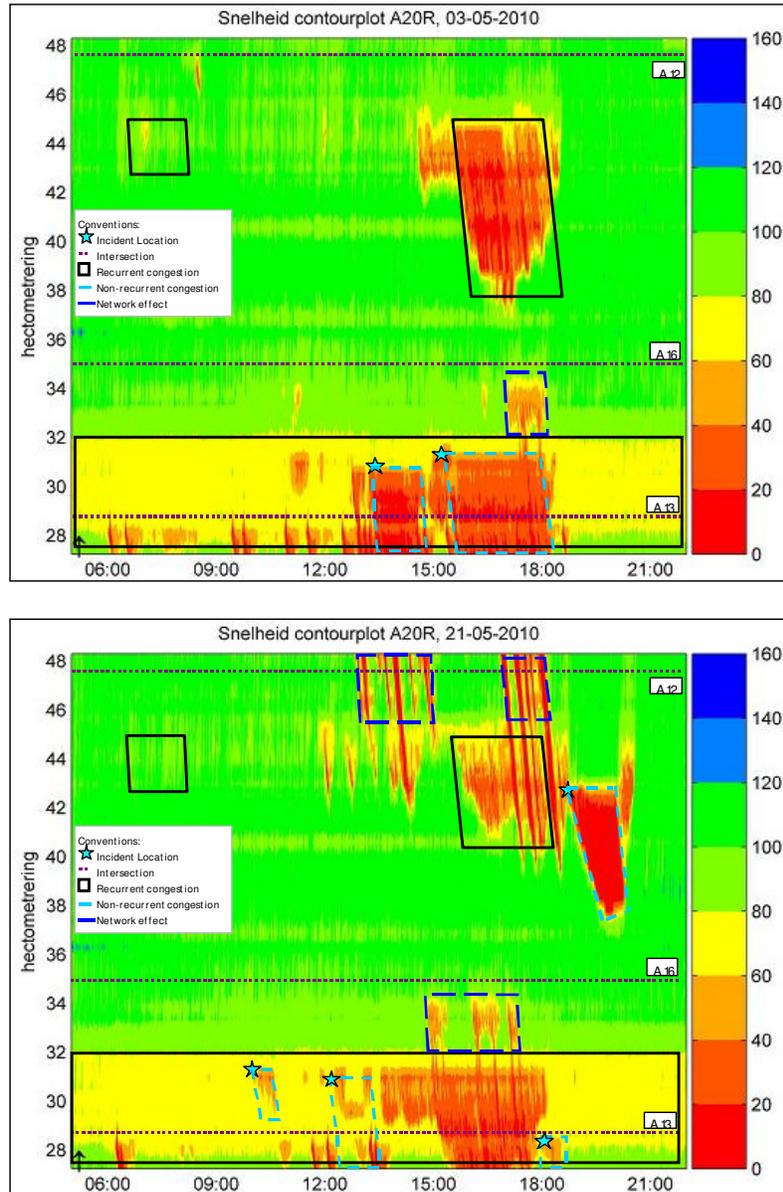
Figure 5.13: Speed contour plots for the A20 Left direction (Gouda - Rotterdam). Reference day (up) and comparing day (down).



In Figure 5.13 can be seen clearly the concepts explained in the previous section, with regards to the complex behavior of recurrent delays. As it was mentioned in the case for the A13, here the sections close to the intersection present delays (travel below the reference speed of 80 km/h) the whole day. Similarly to the case of the A13, here can be seen the incident locations and the resulting delays. It has to be mentioned that the incidents near hectometer 28 and 31 at AM period (May 7<sup>th</sup>) result in negligible delays. The rest of the incidents have zones in dashed blue lines indicating extra delays produced. Again, the yellow and red parts that are not surrounded by any line, belongs to other causes of delays.

The results for the right direction (Rotterdam - Gouda) are presented on Figure 5.14. The reference day was compared against May 21<sup>st</sup>.

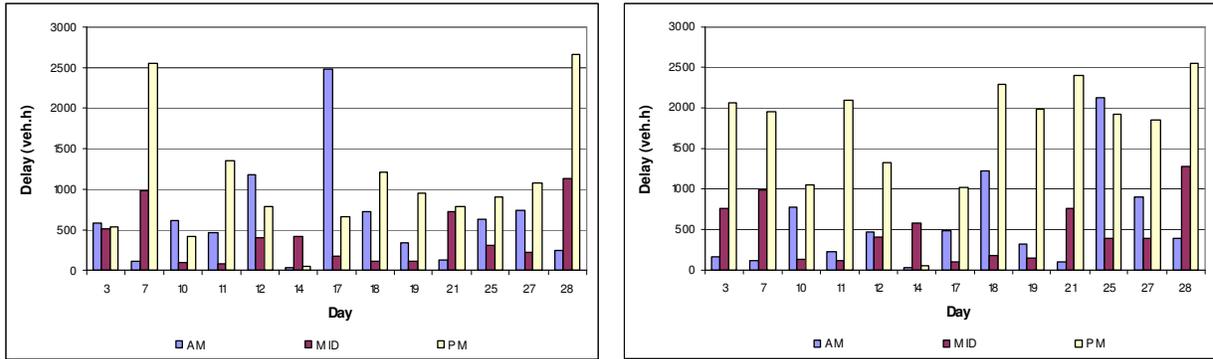
Figure 5.14: Speed contour plots for the A20 Right direction (Rotterdam - Gouda). Reference day (up) and comparing day (down).



In the Figures above can be seen that the recurrent congestion zones match approximately with those of the left direction, especially the zone of the intersection with the A13 and during the PM peak period in the stretches comprised hectometer 42 and 46. For May 7<sup>th</sup> is clear the zone resulting of one incident and the network effects in the zone of the intersection with the A16.

The analysis of the  $D_{total}$  for the AM, MID and PM periods for left and right direction are shown in Figure 5.15

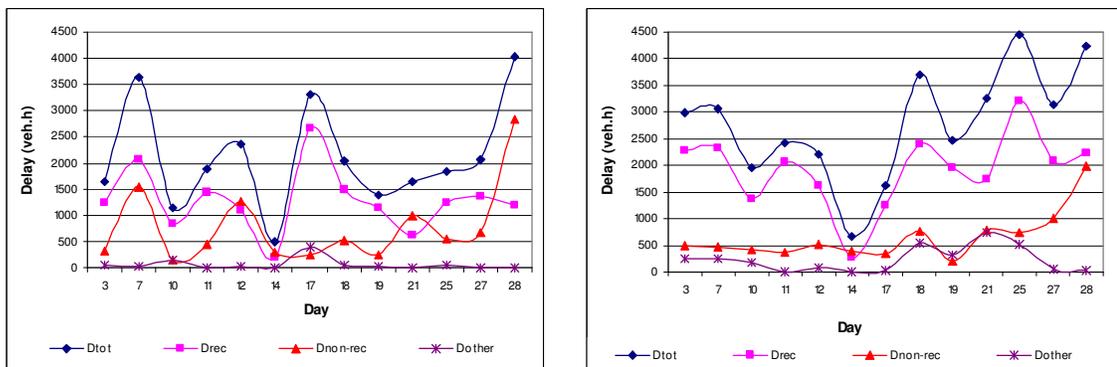
Figure 5.15: Total delay A20. Left and Right direction per period of the day



In the figures above can be seen that delays tend to be concentrated on PM periods, even though there are a couple of days in which the results were bigger on the AM period. This was expected as it was mentioned above, recurrent delays zones are bigger in the PM period for both directions. The delays computed for both directions are comparable, with the peak values near to 2500 veh.h.

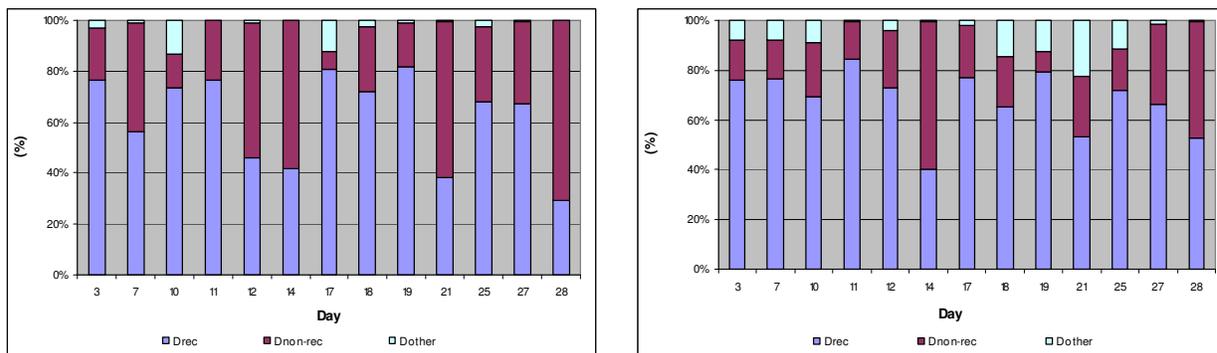
These total delays  $D_{tot}$  were decomposed in  $D_{nonrec}$  and  $D_{other}$  for the A20 (whole days) for the period analyzed. It is presented in Figure 5.16.

Figure 5.16: Delay decomposition for the A20. Left and Right direction



In Figure 5.16 was perceived that total delays are guided mainly by recurrent delays. For the left direction  $D_{nonrec}$  has a bigger participation in the total value than in the right direction. It is also noticeable the fluctuations day by day of the delays, especially recurrent ones that is the expected to behave more even. The share of the total components mentioned in  $D_{tot}$  is presented in Figure 5.17.

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**Figure 5.17: Share of different factors in total Delays for the A20. Left and Right direction**



Surely the biggest share on delays is originated on recurrent ones. Likewise the A13, all the non-recurrent sources of congestion for the A20 in weekdays were incidents. The computed (statistical) parameters for the delays resulting from those incidents are listed on Table 5.4.

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**Table 5.4: Incident analysis per direction for the A20**

|                          | Left Direction | Right Direction |
|--------------------------|----------------|-----------------|
| Number of Incidents      | 53             | 42              |
| $D_{nonrec}$ Sum (veh.h) | 9261.0         | 5400.3          |
| Delay average (veh.h)    | 174.7          | 128.6           |
| Delay Standard deviation | 400.5          | 140.7           |

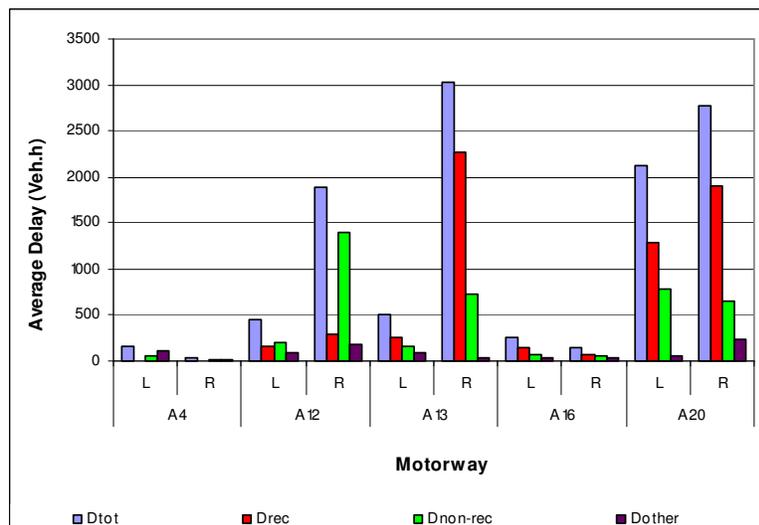
In this table is noticeable that the sum of the extra delay caused by the incidents in the left direction is not comparable with that of the right direction, as the second is about half of the first. However the incident average delays are similar for both directions. The standard deviation for the left direction is about twice as big as the average value. As it was explained before it is attributable to the scattered results.

Regarding to network effects, they had a bigger share for the right direction. They were noticed that the biggest part of them came from the A16, and in less quantity from the A12. As it was mentioned, the intersection zone with the A13 was detected as recurrent delays and therefore no network effect were obtained there.

### 5.3.3 Summary Results

Even though the detailed analyses were presented only for the A12, A13 and A20, there are results for the whole set of motorways included in the study area. In this section are presented the results aggregated for all the analysis period. First Figure 5.18 presents the average delays obtained for all the motorways, in the different elements explained above: total delays, recurrent delays, non-recurrent delays (resulting from occurrences in the database), and non-recurrent delays caused by other sources.

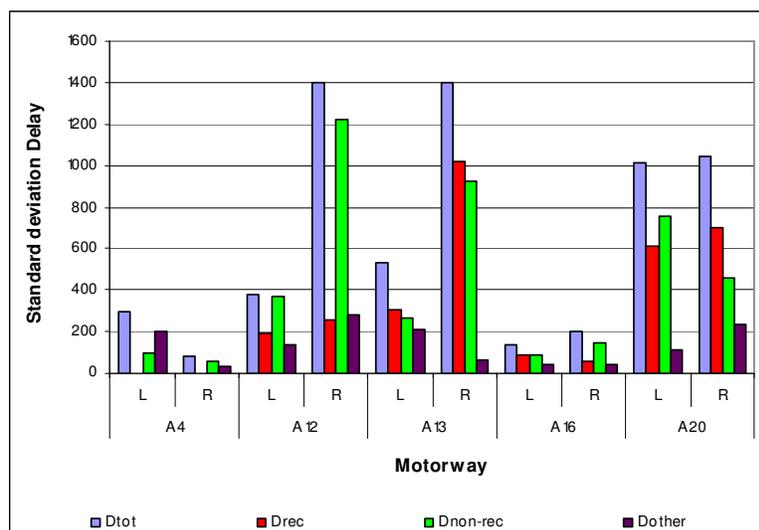
Figure 5.18: Average delays and its components per direction, for all the motorways in the study area



It has to be said that the values presented in Figure 5.18 resulted from average the quantities over the days (i.e. summing up the delays for all days divided by the number of days) and evidently they are different than those values presented in the previous section. Figure 5.18 shows the reason to select the A13 and the A20 for further analysis, as it is clear that they present the highest mean values. Based on the information above it can be inferred that the highest values of total delay are led by recurrent delays, except for the A12 right direction.

To see the dispersion of the data presented, it was made Figure 5.19, with the standard deviations of the previous values. By comparing Figure 5.18 and Figure 5.19 it is possible to see that the standard deviation is usually (for most of the motorways) lower than the average value for total and recurrent delays, and in the same order as the mean for non-recurrent delays. Furthermore, the standard deviation for the A13 and A20 are lower than the mean, unlike the results presented above.

Figure 5.19: Standard deviation of the delays and its components per direction, for all the motorways in the study area



The summary of the occurrences that cause extra delays (non-recurrent congestion) that were found within the databases is presented in Table 5.5.

Table 5.5: Summary of the occurrences that cause extra delays per direction for all roads

| Motorway | Direction | Road Length (km) | Occurrence | Average delay (veh.h) | Standard deviation |
|----------|-----------|------------------|------------|-----------------------|--------------------|
| A4       | Left      | 12.6             | Incidents  | 8.1                   | 10.3               |
|          | Right     | 12.6             | Incidents  | 10.3                  | 7.7                |
| A12      | Left      | 22.5             | Incidents  | 243.7                 | 339.4              |
|          | Left      | 22.5             | Weather    | 0.6                   | 0.8                |
|          | Right     | 22.5             | Incidents  | 33.2                  | 58.5               |
|          | Right     | 22.5             | Weather    | 44.9                  | 88.6               |
|          | Right     | 22.5             | Roadworks  | 345.1                 | 684.2              |
| A13      | Left      | 16.0             | Incidents  | 61.2                  | 105.5              |
|          | Right     | 16.0             | Incidents  | 305.6                 | 393.8              |
| A16      | Left      | 2.5              | Incidents  | 35.5                  | 51.5               |
|          | Right     | 2.5              | Incidents  | 140.8                 | 138.4              |
| A20      | Left      | 21.5             | Incidents  | 174.7                 | 400.5              |
|          | Right     | 21.5             | Incidents  | 128.6                 | 140.7              |

The table above shows that the highest values of the average non-recurrent delay are in the A12 and A13. As it was expected, these values are the same than those presented above in the incidents analysis for the A13 and A20. Table 5.5 confirms that the standard deviation of the delays for non-recurrent events use to be greater than the average values, unlike the total and recurrent delays.

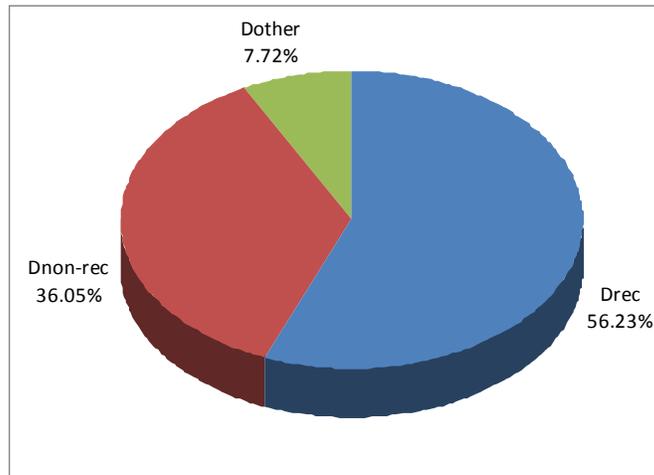
Comparing values in Table 5.5 with those reported on Table 2.5, it is noticed that the average incident delays obtained in the case study for the Netherlands, are in general lower than those values reported by the reviewed papers in the United States (where all of them were carried out). Although it also has to be said that the average delay per incident presented in Kwon et al. (2006) and average delay per collision presented in Kwon & Varaiya (2005) are about half of the average delay of the day, which is considered too high. Only the average delay per accident of 86 veh.h presented in Recker et al. (2005) is lower than most of the values found in the case study, presented in Table 5.5.

The summary of the whole set of delay values, aggregating the data for all the motorways (including both directions) as well as for the time analyzed in the case study is shown in Figure 5.20. It presents the results for recurrent delays, non-recurrent delays with known causes and non-recurrent delays that no cause was found in the data. Based on the results presented in Figure 5.20 it is possible to assert that recurrent delays have the biggest share with more than 50% of the total. Other (non determined) non-recurrent causes of congestion account for less than 10% of the total.

As it was mentioned, among the reasons to obtain these zones that are classified as other delays is that there were found some zones in which exist bottlenecks and it is not reported in any database. Another reason is that the recurrent congestion is present approximately at the same sections at the same time of the day, but it obviously does not always match perfectly all the days. Therefore they have slight variations both

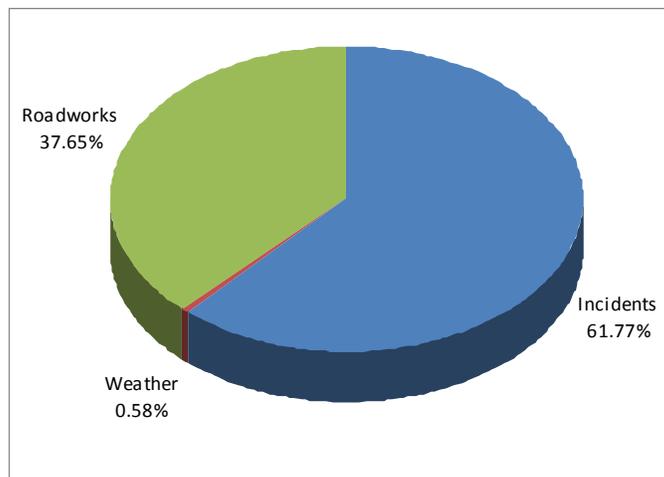
in time and in space, making that they are not reported as recurrent congestion but rather classified as other causes.

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**Figure 5.20: Summary of the results**



The last reasons found to classify delays as 'other' was faulty inductor loop sensors (explained in chapter 4) and shockwaves delays originated outside the study zone. In the results of the case study it was also observed that there were delays resulting from spillback effects (moving jams), surely originated further than the boundary of the study zone. Of course, they original explanation cannot be detected in the algorithm and they are classified as other delays. This is considered that this effect is virtually unattainable. The remaining 35% of the non-recurrent delays (in Figure 5.20) were in turn split in the different components discussed throughout the report, as it is presented in Figure 5.21.

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**Figure 5.21: Decomposition of non-recurrent delays**



Among the different components of non-recurrent delays, incidents presented the biggest share in the case study. Taking into account that only one motorway had roadworks (and in only one direction) it is remarkable that its share is about 40% in the value of non-recurrent delays. The adverse weather conditions had a minor effect, with less than 1%.

Comparing the results of Figure 5.20 with those in Figure 1.2, it is clear that the biggest share in total delays is recurrent congestion, although in the case study the share was lower than the value presented in the problem definition. Other similar results in Figure 5.20 and Figure 1.2 are the share of the weather conditions, with less than 1% of the total, and among the non-recurrent causes of congestion incidents the one which had the biggest percentage in the case study were incidents. Naturally this methodology is the base to make the more accurate the results presented in Figure 1.2, but still is necessary more information that includes the whole country to make a better assessment of the accuracy and compare of the results presented there.

Contrasting the results in Figure 5.20 with the values reported in Table 2.5, it is noticed that the share of non-recurrent delays in the total delays, found in the case study, are higher than those reported in the literature. It may be originated in the fact that most of the papers reviewed in section 2.3.2, considered only one cause of non-recurring congestion, which was not the case in this study. This 36% of non-recurrent delays is comparable with the values reported in Hallenbeck et al. (2003), even though the range there is too broad.

#### 5.4 Sensitivity Analysis

The sensitivity analysis is used to determine how susceptible the model is to changes in the value of the parameters of the model and to changes in the structure of the model (Breierova & Choudhari, 1996). This section focuses on parameter sensitivity. As it was mentioned in section 4.3, in step 4 two threshold values were used, being the percentage of days with congestion in the period analyzed and reference speed (delay threshold). They were changed in order to observe their impacts on the delay outcomes, as presented in Table 5.6.

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**Table 5.6: Sensitivity analysis threshold values**

| Case     | % Congestion | Reference Speed (km/h) |
|----------|--------------|------------------------|
| Original | 50           | 80                     |
| Case 2   | 60           | 80                     |
| Case 3   | 40           | 80                     |
| Case 4   | 50           | 100                    |
| Case 5   | 50           | 50                     |

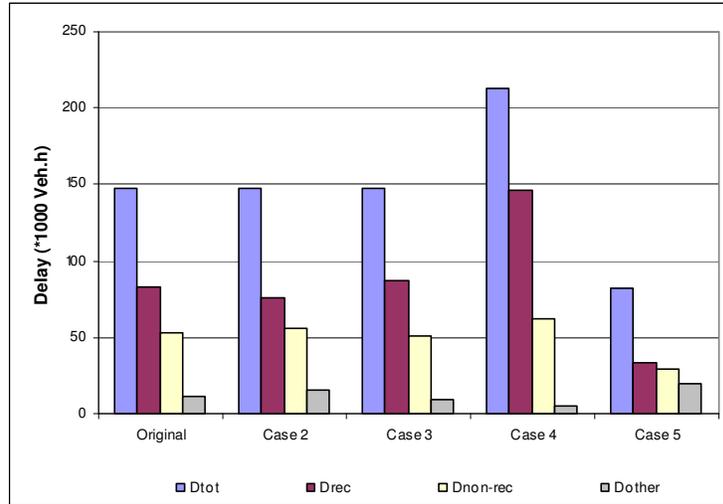
In Table 5.6 the first row corresponds with the original values used in the methodology in section 4.3, and the different set of values are referred to as cases. As the intention is to observe the impact of each parameter in the model outcomes, then in every case the values were varied one at once, firstly rising and then lessening. The first parameter took into account was percentage of congestion considered as recurrent congestion, which in case 2 was increased to 60% and in case 3 it had a value of 50%. After that, the reference speed was set to the speed limit (100 km/h) and then reduced to 50 km/h, which is defined as the congestion onset in the Netherlands.

Clearly, the outcomes of interest of the model (and therefore will be studied) are the different kinds of delays analyzed all over this chapter: total delay, recurrent delay, non-recurrent (known causes) delay, and other delays. The following part of this section is looks more in detail into each delay component, beginning with total delays.

### Total delays

The variations of the absolute values of total delays along with their different components are presented in Figure 5.22. On the vertical axis the delay values are presented, in thousands of vehicle hours.

Figure 5.22: Delays variations in sensitivity analysis.

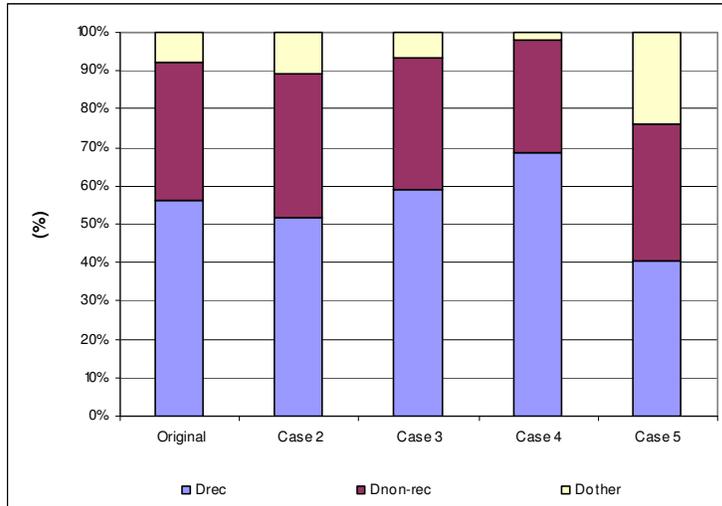


As one might expect, in cases 2 and 3 there are no variations in  $D_{tot}$  with respect to the original values, due to the definition of delay given in chapter 2 (additional vehicle-hours traveled driving below free flow speed  $v_{ref}$ ), since the reference speed value did not changed in these two cases. As a matter of fact the change was in the distribution of the total in recurrent, non-recurrent and other delays. In contrast, in cases 4 and 5 the reference speed was shifted, resulting in an increase of 44% for case 4 and a reduction of 44% in the total delay values. These variations are mostly explained in changes in  $D_{rec}$ , which in case 4 raised 75% (about 63000 veh.h extra) and in case 5 fell 60% (50000 veh.h less).

Similarly to the synthesis presented in section 5.3.3, the information for the total delays were aggregated for all the motorways including both directions and calculated the participation of the different parts in total delays (as shown in Figure 5.20), for the cases of the sensitivity analysis. Then, the portion of  $D_{rec}$ ,  $D_{nonrec}$ , and  $D_{other}$  in  $D_{tot}$  for all the cases is shown in Figure 5.23. As it may be seen, the share of  $D_{nonrec}$  in  $D_{tot}$  is the most stable of the factors analyzed, and its participation ranges between 30 and 40% of the total delays. The larger percentual changes are originated in recurrent and other delays, especially for cases 4 and 5, where the share of recurrent delays varies from almost 70 to 40% and other delays between 2 and 25%, respectively. It can be explained as a result of the augment (with respect to other cases) of

the recurrent congestion zones in time and spaces for case 4, as is explicated below. Then, the algorithm classifies and reports many sections as recurrent delays. It happens the other way around for case 5, where the speed is not below 50 km/h in the same road sections at the same time of the day (to be reported as recurrent congestion).

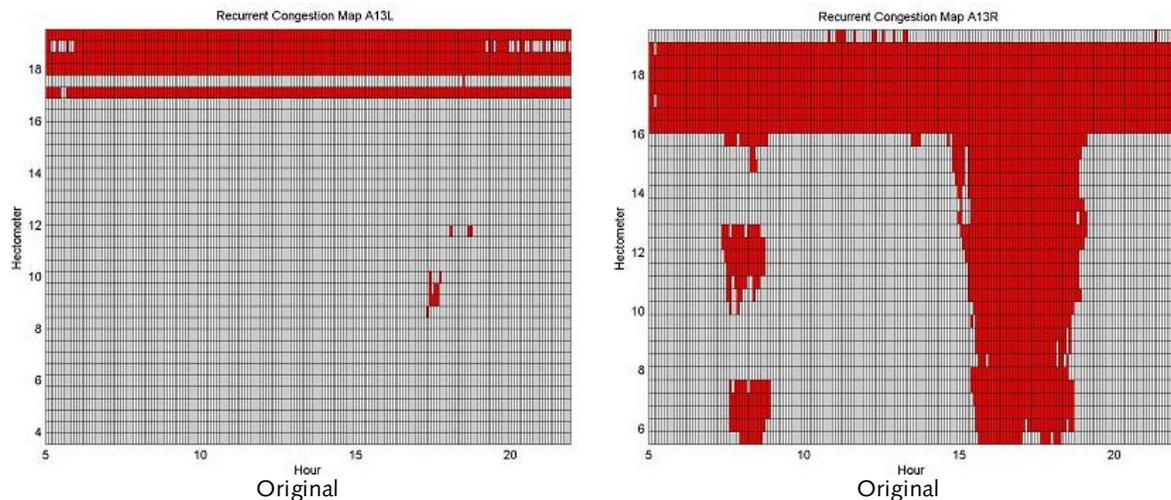
Figure 5.23: Shares of  $D_{recr}$ ,  $D_{nonrecr}$  and  $D_{other}$  in  $D_{tot}$  for all the cases

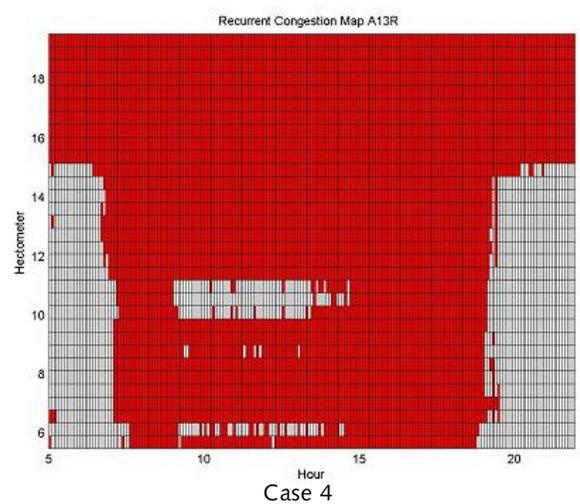
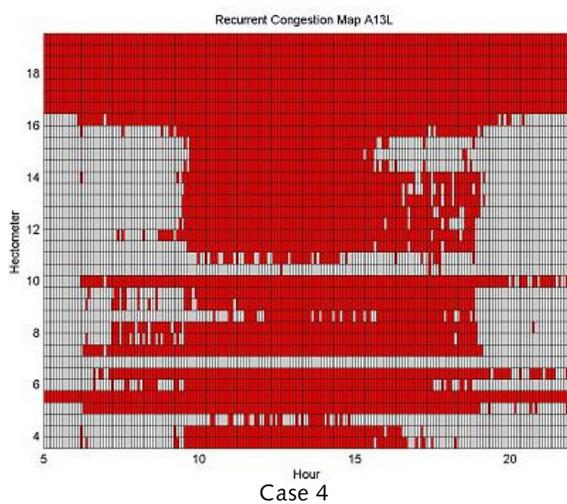
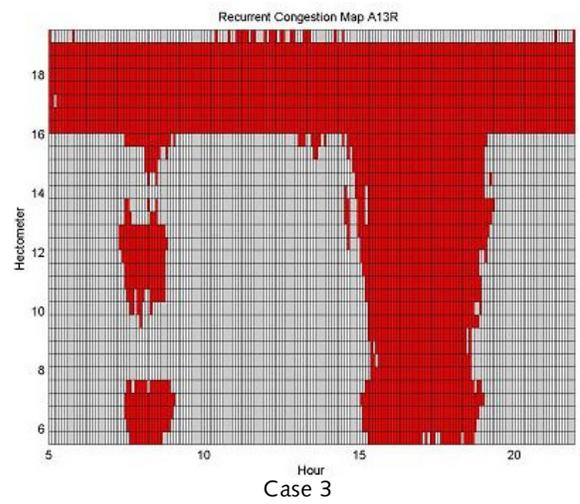
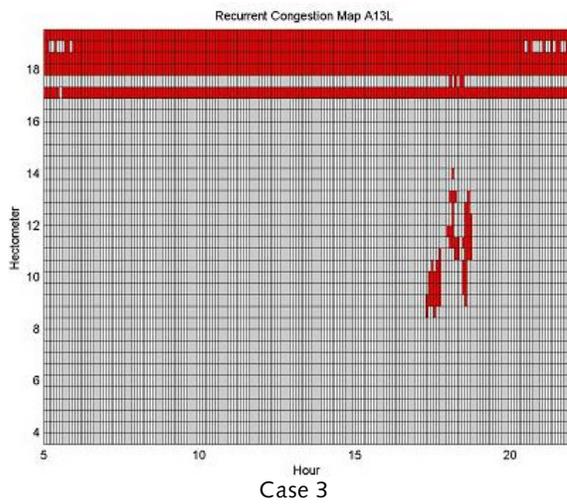
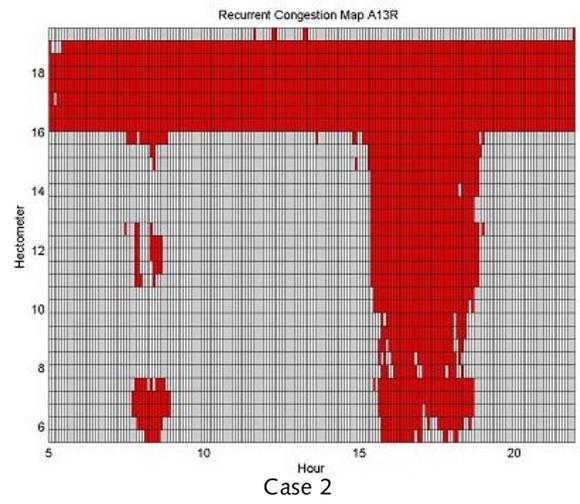
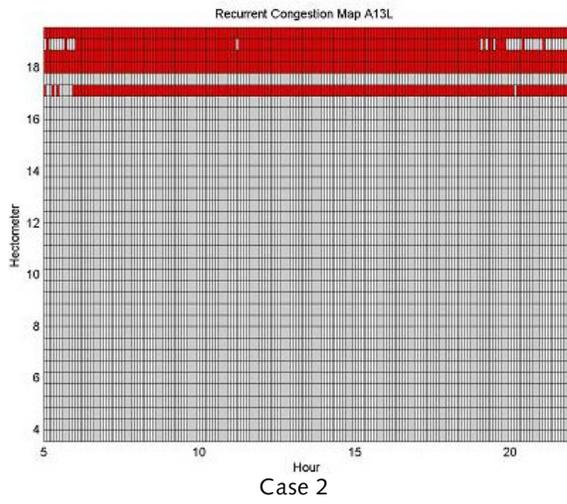


### Recurrent delays

As in section 5.3, this part only includes those motorways with the highest delays being the A13 and the A20. For these two motorways it was drawn the recurrent congestion maps, that is, the 'recurrent congestion segments' RCS described in section 4.3 (marked in red), for the cases presented in Table 5.6. It has to be said that in these 'recurrent congestion maps' the shockwaves mentioned in section 4.3 were not included. The recurrent congestion maps are presented in Figure 5.24 for the A13 (left and right direction), and in Figure 5.25 for the A20 left and right direction.

Figure 5.24: Recurrent congestion maps A13, left and right directions





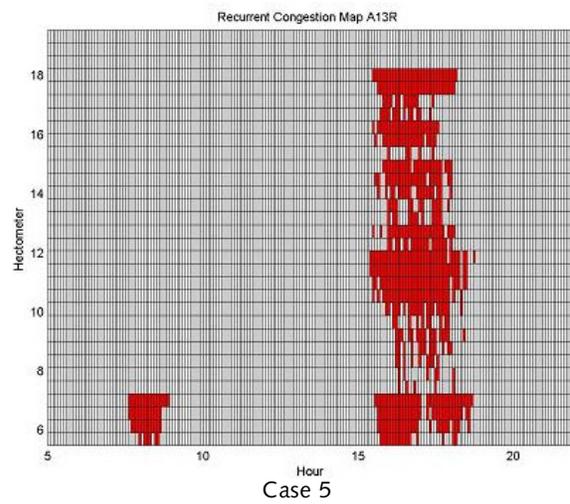
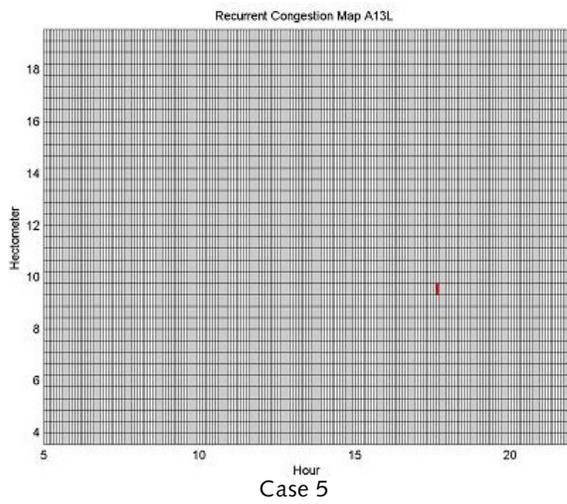
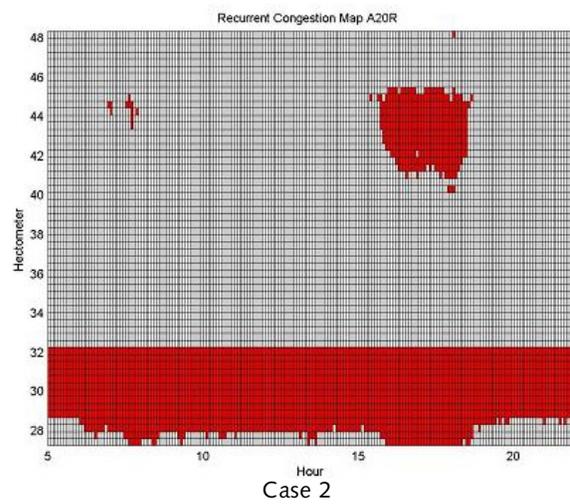
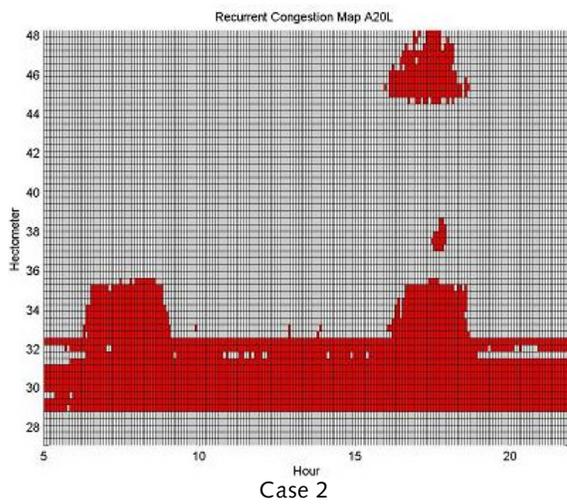
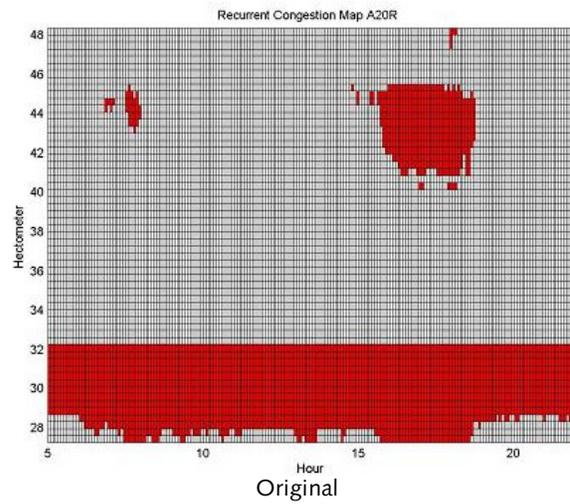
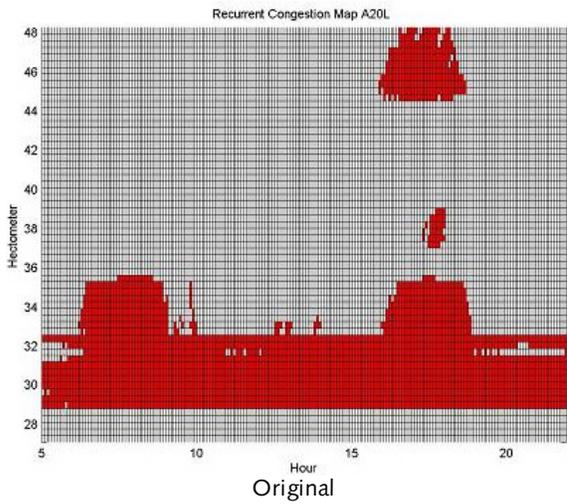
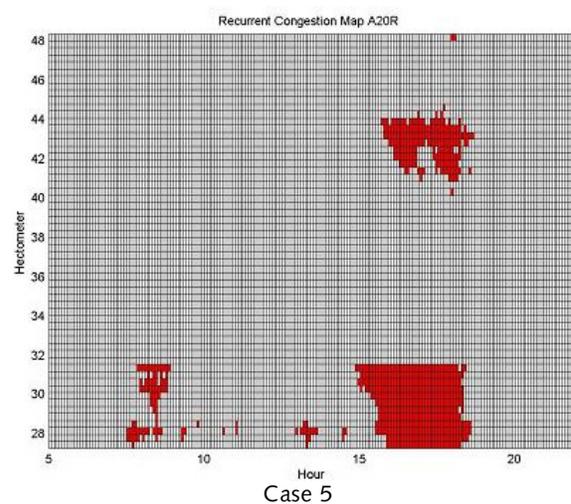
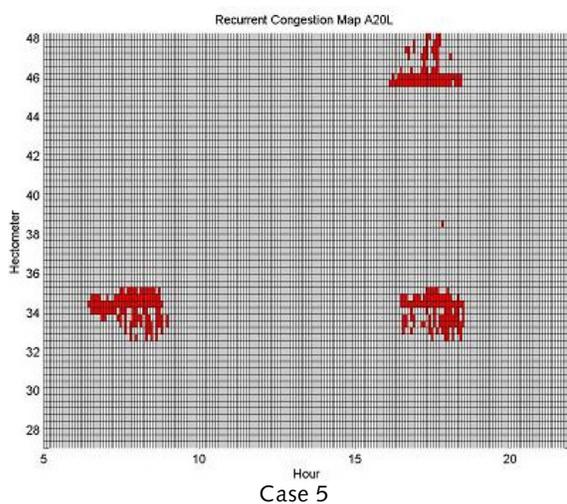
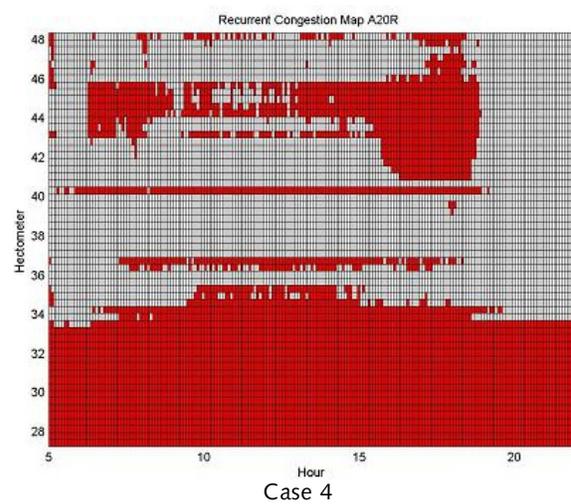
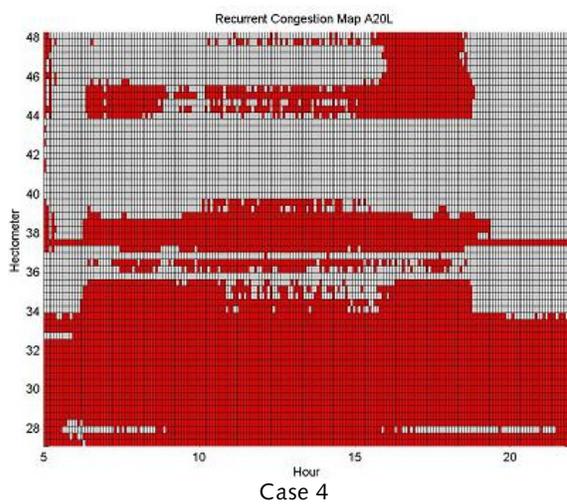
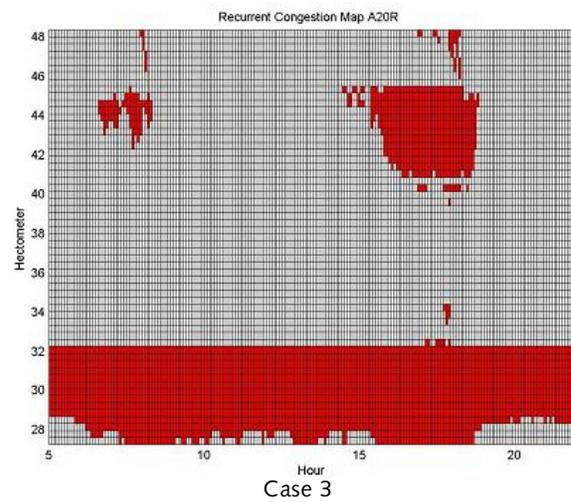
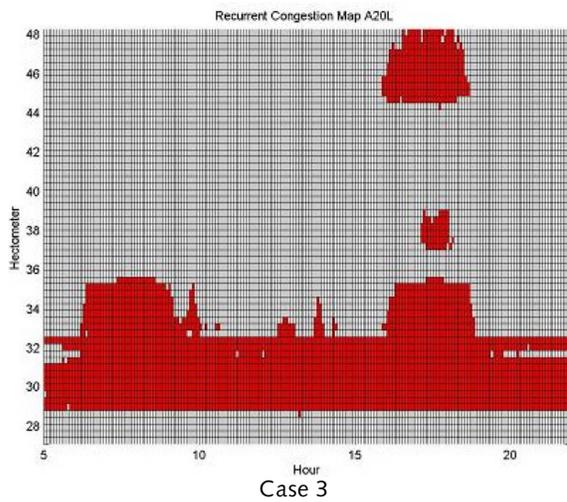


Figure 5.25: Recurrent congestion maps A20, left and right directions





As it may be seen in these figures, variations in extension in time and space of the recurrent congestion zones for the motorways analyzed were slight: minor decrease in case 2 and minor increase in case 3, comparing with the original case. For instance, the recurrent congestion zone present in the neighborhood of hectometer 44 between 6 and 7

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h, for the A20 right direction (Figure 5.25). This recurrent congestion zone almost vanishes in case 2 and grows in case 3.

Quite the opposite situation occurs in cases 4 and 5, where the changes in the recurrent congestion maps are strong. If the reference speed is increased, it implies to consider many speed values as delays, and it explains the existence of some sectors that have delays almost the whole day, especially for the A13. It has to be taken into account that the lower part of the maps for the A20 (approximately between hectometers 28 and 32) consists of a zone with a speed limit of 80 km/h, which is reported as delays by the algorithm, in case 4. The recurrent congestion maps for Case 5 show the zones that use to present speed values below 50 km/h, and naturally they are less than in the other cases studied. For example for the A13 left direction there is almost none. The mentioned zone in the A20 with the speed limit between hectometers 28 and 32, exhibits a region of recurrent congestion in case 5, amid 15 and 18 h.

To sum up, it was noticed that the methodology outcomes for recurrent delays are especially sensitive to the value of reference speed, rather than the percentage of days with congestion in the period analyzed. It was expected that it behaves the other way around, since the percentage of days with congestion in the period analyzed is directly correlated with the definition of RCS and therefore with the calculation of recurrent delays. This can be explained as the reference speed is the boundary that defines delays, and obviously if it is increased, more speeds are classified and reported as 'delays'. Despite this oscillation in the results of recurrent congestion segments shown, it is considered that the methodology is working properly. When the reference speed value was changed, the outcome delays varied consequently. Hence, the final result is highly dependant on the criterion utilized by the user of the methodology: what he or she considers as delay and what is not. Consequently this value should be carefully selected.

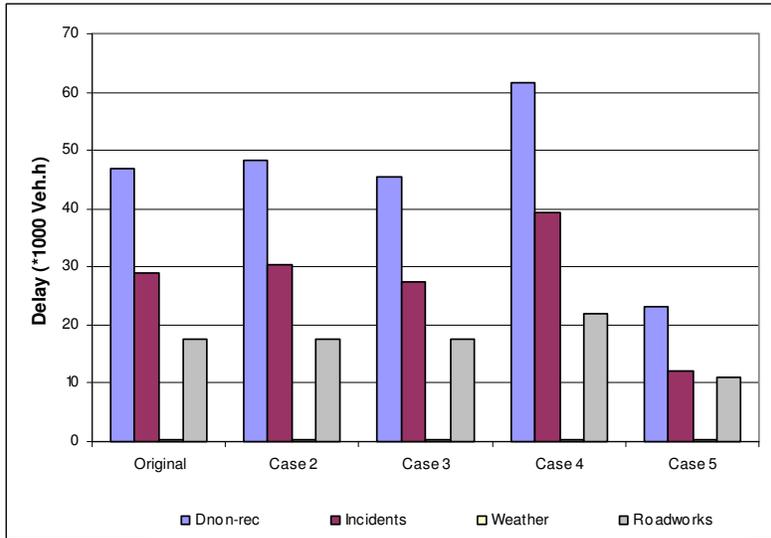
### **Non-Recurrent delays**

The variation in the values of the non-recurrent delays along with the different causes found in the databases (incidents, adverse weather conditions and roadworks), summing up the results obtained for all the motorways studied (in both directions), are presented in Figure 5.26. The vertical axis presents the delay values in thousands of vehicle hours, and the values of  $D_{nonrec}$  are the same as those presented in Figure 5.22.

As it may be seen, the results obtained for cases 2 and 3 are quite close to those of the original run. Variations in the value of  $D_{nonrec}$  in both cases are originated in differences in delays caused by incidents. They are originated in the fact that in this part measures extra delays caused by non-recurrent events. Given that recurrent congestion areas were increased (for case 3) in some sections, the delays were split between recurrent and non-recurrent causes. As the sections that overlap

between recurrent and non-recurrent delays are mainly caused by incidents, the effect is noticed mainly in this item.

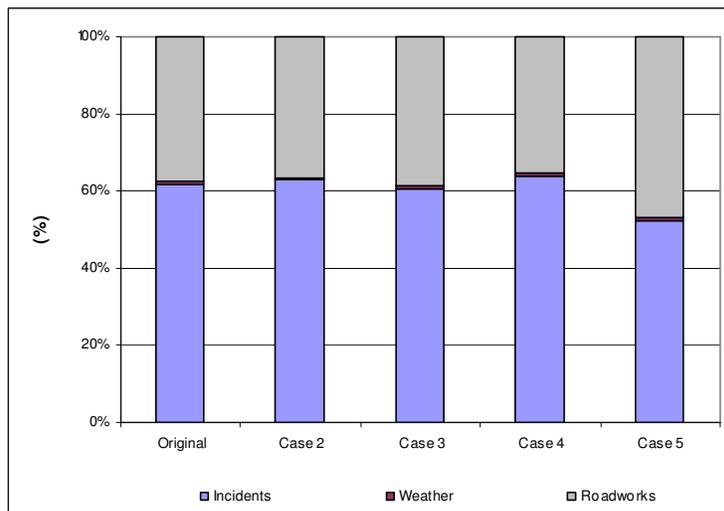
Figure 5.26:  $D_{nonrec}$  variations in the sensitivity study with its components



Again, cases 4 and 5 show large differences in their values, compared with the reference situation. This effect is produced for the same causes discussed above (change in reference speed imply change in delay definition) and thus are not repeated here. Notice that the results obtained for adverse weather conditions are marginal, even in case 4 where the values are the highest among the cases studied.

The share of incidents, adverse weather conditions, and roadworks in the  $D_{nonrec}$  value is presented in Figure 5.27. In this figure it can be seen that although the absolute values had variations, the share of the different components is approximately stable. Incidents have the biggest share (around 60%), except for case 5, where their share drop to almost 50%.

Figure 5.27: Shares of different causes in  $D_{nonrec}$



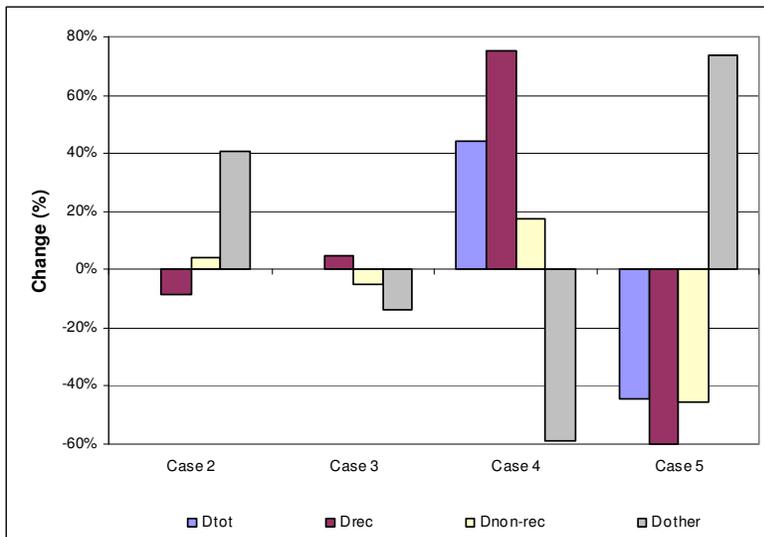
### Summary

All the delay components analyzed throughout the report ( $D_{tot}$ ,  $D_{rec}$ , and  $D_{nonrec}$ ) were already aggregated and presented above in total delays analysis (Figure 5.22 and Figure 5.23). Therefore this part is focused rather in the changes in percentage of the variables studied, as a result of the changes in the input parameters, listed in Table 5.6. The changes in percentage (regarding to the values of the original case) obtained in the sensitivity analysis are rounded up in Table 5.7, which also lists the input parameters. This information can also be seen graphically in Figure 5.28.

Table 5.7: Summary of results sensitivity analysis

| Case | % Congestion | Reference Speed | $D_{tot}$ | $D_{rec}$ | $D_{nonrec}$ | $D_{other}$ |
|------|--------------|-----------------|-----------|-----------|--------------|-------------|
| 2    | 20.0%        | 0.0%            | 0.0%      | -8.4%     | 4.5%         | 40.6%       |
| 3    | -20.0%       | 0.0%            | 0.0%      | 5.0%      | -4.9%        | -13.8%      |
| 4    | 0.0%         | 25.0%           | 44.3%     | 75.6%     | 17.5%        | -58.6%      |
| 5    | 0.0%         | -37.5%          | -44.5%    | -60.0%    | -45.6%       | 73.5%       |

Figure 5.28: Summary of results sensitivity analysis



The figure and table above showed that the percentage of days with congestion in the period analyzed have an effect on the distribution of the different delays components. As it was mentioned, in cases 2 and 3 there were no changes in  $D_{tot}$ , and there were only changes in the distribution of the different components. It was shown that the higher the percentage of days with congestion, the lower the outcome of recurrent delays, although in a different amount (an increase in 20% in the first, produce a decrease of 8% in the second). This change is compensated by a change in non-recurrent delays (with either known or unknown cause), as it may be expected.

Changing the reference speed, which is the boundary that defines the speeds that are considered as delays, has a larger impact on the results, compared with the percentage of days with congestion. In case 4, an increase in 25% in the reference speed brought about an augment in total delays of 44%. As it was described, the biggest part of it was

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originated in the boost of RCS. Case 5, where reference speed was diminished 37.5%, resulted in a reduction of total delays of 44% (almost the amount as in case 4). This value has also a big impact on in the non-recurrent delays that are classified as  $D_{other}$  as was explained before.

Based on the information presented above it is possible to deduce that the outcome delays are more sensitive to changes in reference speed than in percentage of days with congestion. In the same manner as traffic modeling programs, where the input values should be chosen using the criterion and expertise of the user, the selection of the input parameters in the algorithm designed should be carefully done, especially the reference speed.

It was observed that the results obtained setting the speed value to the speed limit (100 km/h) were extreme high and in the case of 50 km/h were extreme low. Therefore it is considered that that the initial reference speed value of 80 km/h is adequate, and thus is recommended to use it in future applications. With regard to percentage of days with congestion, based on the results of the sensitivity analysis, it is considered that 50% or 40% are suitable values.

## **5.5 Method considerations**

Throughout this chapter it has been shown the way in which the developed method worked. In section 4.5 it was corroborated that the method works properly assessing and decomposing delays (total, recurrent, etc). This method is flexible in terms of possibility to include additional causes of non-recurrent congestion and in possibilities to aggregate and analyze the outcome data. Nevertheless, in the validation process, case study, and sensitivity analysis, it was found that the methodology has some drawbacks as well. This section has the aim to look at these drawbacks critically and to propose some actions that may be undertaken to face them, which at the same time are recommendations for future research. The second part makes the same (critical assessment of drawbacks and proposed solutions) with the computer tool described in section 4.4. In the final part of the section one last consideration about the method is made, regarding to the way in which the methodology considers how recurrent delays may be affected by the presence non-recurrent events upstream.

### **5.5.1 Methodology evaluation**

In the developed methodology were found some shortcomings, which are described in the following.

In first instance, the developed method has a unique value of reference speed, for all the motorways stretches and the analysis period. This fix value makes the methodology less robust, as it cannot cope with

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changes in some parts of the network. For instance, these motorway sections where the speed limits are 80 km/h (instead of the usual value of 100 km/h), the methodology could misinterpret that and report congestion. For future research it is recommended to look for a technique that lets introduce different reference speed values for different parts of the network (or motorways sections), in order to reflect this differences.

The way in which the methodology handles incidents is considered another weak point. As they are included all in the same database (IM), the methodology does not differentiate among the severity of the occurrence (e.g. number of lanes blocked). Therefore the outcome delays are scatter with large standard deviation values, close to the mean values. In order to diminish this effect, it is proposed to explore the option of classify beforehand the incidents in the IM database, according to the severity of the occurrence: e.g. number of lanes blocked, duration of the blockages, et cetera. Based on these criteria the database could be split, and hence the input would be several databases instead of one.

It was noticed during the algorithm validation in section 4.5 that there were some discontinuities in the measurements of the inductor loops detectors, which led to wrongly classify some part of the delay. Looking at the graphs in the mentioned section for the A20 right direction, it is clear (as it was commented there) that one part of the delay belongs to 'recurrent delay' and appears in 'other delay'. Therefore the algorithm is sensitive to these discontinuities. This is considered that the filtering process should prevent it to happen. Consequently it is recommended to develop a project that incorporates the filters in the data retrieving process from Monica database (Monigraph interface).

During the case study it was noticed that in the zone of the roadworks there were often congestion in the left lane (see Figure 5.2), although the roadworks were carried out in the right direction. However this effect was present during different hours of the days within the analysis period and only a small zone was reported as recurrent congestion. In general, these delays were classified as other causes. They may be attributable to rubbernecking effects, nonetheless there is not enough evidence to support this hypothesis. The methodology misses to explain these kind of occurrences.

### **5.5.2 Computer tool evaluation**

The computer tool developed results were tested (validated) at the same time than the methodology itself. Thus it was shown that this computer tool works properly as well as the methodology. Yet it is its first development, then it would be improved, like it used to happen with any software development. It was noticed that the computation time is large, and the user interface is still not friendly enough. The outcomes are basically the cubic 3D matrices described in section 4.4, which contains all the data, but the data aggregation process, which is

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the base of the results shown in this section, were made in a separate module. It was the case not only for the data (numbers) but also for the graphs presented. It was especially noticed in obtaining the final cause of congestion in the case of network effects, which had to be done 'manually' as the process is not automated yet.

Based on the above-mentioned aspects, it is considered that the new releases of the computer tool should try to find a way to improve the routines to reduce the computation time, the user interface in order to make it more user friendly, and automate the procedures of compute the results and obtain the final cause of network effects.

### **5.5.3 Influence of non-recurrent events in the results of recurrent congestion**

As it was mentioned before, the last part of this section is dedicated to evaluate possible influences of non-recurrent events in the recurrent congestion downstream. That is to say the cases when one non-recurrent event brings about congestion in a place where is not usual, shifting the congestion location (in time and space) from its usual (recurrent) location to the new bottleneck upstream created by the occurrence.

This effect is grab by the methodology, as it assesses all the delays (total, recurrent, etc). Therefore in case of the described situation occurs, the methodology reports the non-recurrent delays upstream and the recurrent delay downstream. If the last value is compared against these days when no non-recurrent occurrence was present, it would be noticed its reduction. Thus the reallocation of the congestion upstream is registered, although the methodology does not do this automatically. That is, it is not explicitly reported in its outcomes. Therefore, in case the methodology (or the computer tool) user wants to detect this effect, it should be done 'manually'.

In the way the results were presented in section 5.3.2, it is possible to mention some aspects that may indicate that the described effect is present. For instance, look at changes at delay decomposition (e.g. Figure 5.16) and share of different factors in total delays (e.g. Figure 5.17). If it is noticed that the share of recurrent delays in total delays is decreasing at the expense of increasing in non-recurring delays, it could be an indicator of this effect and therefore the data of these days should be examined more in depth. For instance, looking at Figure 5.16 and Figure 5.17 for the A20 left direction, it is noticed that in particular May 21<sup>st</sup> and May 28<sup>th</sup> non-recurrent delays account for more than 60% of the total value. Therefore it is indicating that the shifting in congestion location may be present. Therefore it was dug up in the data of these days, and it was noticed that the mentioned effect is especially noticeable on the 21<sup>st</sup>.

In case of requiring make this process automatically, it is recommended that the first step is to develop a routine that assess simultaneous

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reductions in the percentage of recurrent delays and rises in the percentage of non-recurrent delays. For those days and motorways in which this effect is present, seek if the recurrent congestion zones are indeed diminished as a result of non-recurrent occurrences upstream. Obviously it includes checking if the non-recurrent event was present at the same hour (or just before) as the recurrent congestion.

## 5.6 Conclusions

In this chapter the methodology developed was applied to a case study. It was developed taking real data obtained from the diverse databases described in the report, and results were derived from these real data. The selected area for the case study comprises 5 motorways, and it was considered the left and right direction. This means that there is available 10 datasets of results. Evidently this is an excess of data that is not only unsuitable to be presented, but also annoying for the reader trying to grab them. For this reason the results presented in this chapter were narrowed down, and only the most relevant data was included.

This first thing noticed in the results obtained applying the methodology was that outcome delays tend to be scattered, since often it was found that the standard deviation was as large as the mean values. This is the consequence of compare extreme values (high and low). For instance, the case observed in the A12 left direction analysis, where two incidents overlapped their effects; one brought about a delay greater than 1000 veh.h and the second, less than 10 veh.h. It means a difference of three orders of magnitude in the outcome delay. In order to prevent this, it would be recommended to classify the incidents according to the severity of the occurrence: e.g. number of lanes blocked, duration of the blockages, et cetera, and according to these criteria, split the database. Nevertheless, these scatter results was noticed in roadworks as well, where the resulting mean delay is less than the standard deviation (see Table 5.5). This, despite that the prevailing conditions (lanes blocked, remaining capacity, et cetera) in roadworks are more stable than in other non-recurrent events (e.g. incidents).

These extreme result values are the product of assessing a highly stochastic system, in which intervene a vast amount of factors. For instance, taking the case of the delays analyzed, it may be expected at least they tend to be fluctuating around a value, but in the graphs presented in this chapter it was observed that the results vary between days, reaching even different order of magnitude.

Among the outcomes of the methodology are the time period(s) and motorway sections in which usually congestion is observed. Almost certainly road users and authorities are aware of these locations (in time and space), but probably they are not always measured. The methodology provides hard data about locations, daytime, intensity

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and duration of recurrent congestion, which could be used in other applications.

During the process of assessing the different delay components, it was found that recurrent delays have the largest share, with more than 50% of the total value. This result goes in line with expectations, considering the background information presented during the problem definition in chapter 1. Therefore the evidence shows that the majority of the congestion problems arise in those situations that are present most of the time.

Despite of that, in the case study it was found that the share of the extra non-recurrent delays in the total value is considerable. Among the considered causes of non-recurrent congestion, it was found that incidents are the one that most frequently occur. Yet it was also found that many of them do not bring about extra congestion. Looking at the findings of this section it was found that although roadworks were only present in one of the studied motorways and in one direction, they are still responsible for almost 40% of the recurrent delays obtained in the case study. It also has to be taken into consideration that the expected remaining capacity is 90%. Therefore it is considered that they have important impacts on the mobility, justifying the large efforts made to develop plans to cope with their undesirable effects.

Comparing the results of the average delay caused by incidents computed in the case study with those reported in the literature, it was noticed that they are in the same magnitude order, and they are in between. That is to say, there were found higher average delay values as well as lower. It indicates that the delay values found in the case study are reasonable, as no extreme were found.

Among the causes of non-recurrent congestion, the results obtained for adverse weather congestion were marginal, contrary to the expected. The share in the total results is less than 1%. However, these results may change if more amount of information is included there, and measuring in other season of the year, such as the winter. For instance in snowing conditions the outcomes may be different and be closer to those values presented in the problem definition. Nevertheless it is necessary to have the information about these occurrences.

It was found in the results of non-recurrent delays classified as 'other causes' are higher than expected. In this chapter was shown that part of them is originated in bottlenecks whose cause is not among the databases and therefore they could not have been categorized. The remaining part is the result of effects like shockwaves originated outside of the study area and faulty sensors that miss measures, as was explained in chapter 4.

In the sensitivity analysis was found that the methodology results more sensitive to changes in reference speed than in percentage of days with congestion. In the same manner as traffic modeling programs, where

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the input values should be chosen using the criterion and expertise of the user, the selection of the input parameters in the algorithm designed should be carefully done, especially the reference speed.

It was observed that the results obtained setting the speed value to the speed limit (100 km/h) were extreme high and in the case of 50 km/h were extreme low. Therefore it is considered that that the initial reference speed value of 80 km/h is adequate, and thus is recommended to use it in future applications. With regard to percentage of days with congestion, based on the results of the sensitivity analysis, it is considered that 50% or 40% are suitable values.

The most important outcome of this chapter is that the methodology accurately assessed delays on Dutch motorways caused by roadworks, incidents, and adverse weather conditions, which is the main research objective. Moreover, in this chapter was obtained the percentage of the total delays produced by non-recurrent causes (research question 4). It also found which is motivating most of the non-recurrent congestion (first part of research question 5).

The results presented in this chapter, together with the measures and policies presented in chapter 3 are the base for the next chapter.

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## 6. Policy Recommendations

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After applying the developed methodology to assess non-recurrent congestion to a case study, the next step is to make some policy recommendations in relation to the topics discussed in the whole study.

These recommendations are made aiming to decrease, or at least to mitigate the adverse effects of congestion assessed. Then the outline of the chapter includes first the causes of non-recurrent congestion, ordered according to the weight that they have in non-recurrent congestion outcomes presented in the previous chapter. First incidents are presented, followed by roadworks and finally adverse weather conditions.

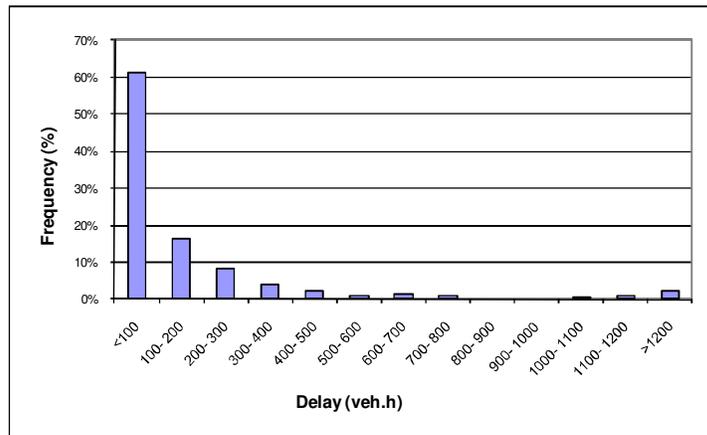
The next part of the chapter gives recommendations in relation to recurrent congestion. As it has been mentioned, one of the results of the methodology was to establish the sections and daytime, which often presents recurrent delays. Then the objective of the last part of the chapter is to give advices regarding this topic.

### 6.1 Incidents

As it was mentioned during the review of the existing policies and measures made on Chapter 3, currently there is an Incident Management plan implemented in the Netherlands. This is the result of several years of experience on this topic. It also entailed large investments and research during this period. The system is well organized and can respond to the situation present in the motorways. In most of the cases reports are made in short periods and the Incident Management plan is started up in less than 5 minutes after the incident took place.

Although the intention is not to make an ex-post analysis of Incident Management measures, it was noticed in the results shown chapter 3 that the outcomes of them are noticeable. For instance, in Table 3.2 was mentioned that the already implemented measures in Incident Management have decreased congestion in about 7%. Most of the incidents cause minor delays and have a marginal impact on traffic operations. Nevertheless there are still some major incidents that have large effects (queues and delays) on the roads, remaining even for hours (Knoop, 2009). The results obtained in the case study are consistent with this, as it was expected. Figure 6.1 show the relative frequencies of the delays resulting from incidents in the case study. It is noticed that the graph is skewed to the left, corroborating that more than 60% of the incidents brought about delays less than 100 veh.h, and it has long tail.

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**Figure 6.1: Frequency analysis delays produces by incidents in the case study**



Due to its stochastic nature, this kind of occurrences are always present in the roads and they cannot be avoided, however their negative impacts on traffic operations could be reduced.

Then in one hand there is a good plan product of big efforts (in time, investments, experts, etc) and in the other hand there are still some undesirable big impacts of few incidents. Therefore the efforts should be directed to those motorways more prone to incidents. The emergency services (tow trucks) should be closer to these motorways and preferably in these vulnerable places of the infrastructure. These places should result from incident rate surveys.

Despite it was not the main purpose of this particular study to find the motorways with high rate of incidents, there was also detected in the outcome data, as was presented in the previous chapter. For instance, looking the number of incidents, it was noticed that the motorways with the highest value were the A20 and the A13, even though they have not the longest stretches within the area under analysis. The longest stretch was in the A12 (22.5 km) and the total number of incidents registered there were 18 in both directions. For instance, in the A20 there were 95 incidents registered causing extra delays. They resulted in more than 400 vehicles hour lost in average, during the evening period, for those travelling direction Gouda-Rotterdam, in the analysis period. In the case of the A13 had, although it presented less amount of incidents (48), they brought about the maximum average delays among the roads analyzed, with more than 500 veh.h for the right direction. Naturally, the significant outcome of these average congested condition levels (delays) every day, are the economical (monetary, time, environmental, etc) loss they lead to.

For both roads the sections (kilometers) with the highest amounts of incidents were in Rotterdam area. These quantities are presented to highlight that most suitable location for the supporting centers, which dispatch the recovery trucks in the area studied, is the Rotterdam neighborhood, since the evidence show that these are the most accident prone links in the network considered.

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It was noticed that most of the efforts are aiming to solve the situation when the incident has already happen. Nonetheless the efforts could also be directed towards prevention. It entails that part of the efforts should look for avoid that the situation that trigger the incident occurs. For instance it is well known the correlation between speeding and incident rate. For that reason policies that encourage drivers to respect speed limits diminish the incident rates, preventing this occurrences happening. Furthermore, these policies are always high cost effective (van Ham, 2008) because they not only prevent loss of time in congestion but also vehicle damages and especially injuries and fatalities.

Other policy in this direction could be promoting drivers make preventive maintenance of vehicles. In this way is avoided car and trucks breakdowns, which is one of the occurrences classified as 'incidents'. Analyzing the IM database for the case study, it was noticed that vehicle breakdowns is the event that most often happens, with about 50% of the occurrences in the database. This policy could be directed to both, personal vehicles and truck drivers and companies that use trucks and lorries as part of their business (e.g. logistics, delivery, et cetera).

Taking into account IM measures undertaken in other countries, it was noticed that some strong points might be implemented in the Netherlands. It was the case in the review of the measures in the United Kingdom, where it was observed that they have already integrated the ITS services on the IM plans. There are two different approaches of ITS in the IM services. The first is related to traffic management measures, where based on the traffic flows at the incident moment, look at the possible alternative routes and assess the impact of diverting traffic flows to them. Based on this, design a response plans to decrease the potential delays. The second approach involves provide information to road users by means of VMS signs, as well as information service providers.

## **6.2 Roadworks**

Almost every equipment and asset requires maintenance to fulfill their functions in the expected level. Poor maintenance could mean shorten in the life of type of the asset. In the case of road infrastructure, maintenance is made by means of roadworks. They intend to maintain infrastructure at is the highest possible service level. Hence roadworks are unavoidable, and they always hinder road users, in certain extent. Chapter 3 gave an overview of the plans developed to mitigate the hindering of roadworks in the Netherlands. Table 3.2 establishes that these measures have decrease demand on roadworks corridor in 11%, diminishing congestion in 38%.

Every roadwork undertaken in the country involves its own mobility management plan. The idea of these plans is to have the lowest

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nuisance level possible. For instance, in order to reduce negative impacts of roadworks, they are often carried out during weekends. These plans are developed by proficient professionals that certainly do their best. Hence it is considered that current methodology, with specific mobility management plans for every roadwork, is already good enough, as shown the ex-post evaluation of Table 3.2.

However, roadworks still have a big share in the non-recurrent delays. For instance, in the case study it was shown that although roadworks were present only in one of the considered motorways, they represent almost 40% of the non-recurrent delays. It implies big impacts on mobility. For this reason it is considered that the proposed traffic management measures (look for alternative routes and evaluate potential impacts of traffic diversions to undertake measures) in the previous section may also apply for roadworks, but in a kind of emergency plan. This will be described in section 6.5.

### **6.3 Weather Conditions**

The final cause of non-recurrent congestion studied in this report, was adverse weather conditions. In the previous chapters was noticed that the information available in this topic involve basically rain. The information available is captured by KNMI weather Doppler radars and transformed in rain intensity. This information is given in a grid that covers the whole country. This grid has been associated with road stretches, making possible to make a geographical correlation between road hectometer and square in the grid.

However, RWS lacks of a tool that retrieve weather information per hectometer of road as such, as MoniGraph tool does. For instance in the case of this work, the dataset has to be built for the case study. Therefore it is considered that this tool should be developed, otherwise the assessing process of non-recurring congestion as was conceived in this study would either become incomplete or take many time. Bearing in mind the knowledge already available and considering the experience with MoniGraph, this task should not be difficult.

Other aspect that need to be improved, and therefore it is recommendable to be implemented is measuring diverse weather conditions. The data available of adverse conditions involves only rain, yet it is not the only weather occurrence that may potentially affect road operations. Other important causes of non-recurrent congestion are snow and fog, and there is no information that correlates them with traffic.

At the present time meteorology is an advanced science that has developed their knowledge in forecast weather conditions. This knowledge has big potential to be included on ITS services, but this big knowledge is wasted. Thus the main advice in this direction is regarding to include this forecast on the different types of ITS, such as on-board

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devices, VMS panels, et cetera. Likewise way that ITS works for decrease non-recurrent congestion caused by incidents and roadworks, it could also work for adverse weather conditions, increasing their benefits. ITS giving advice regarding adverse weather conditions could have an effect on choices such as departure time, mode, and destination, among many others. It could even made that people cancel those trips that are not essential due to delays caused by adverse weather conditions. Again, it based on the meteorological services already quite developed.

As it is well known, the quality of the results of any model is directly related with the quality of the input information. Naturally for the methodology developed to assess non-recurrent congestion it is also the same. Therefore it is considered essential for the quality of the results the improvement of the database available for adverse weather conditions. If the policy advice is that the weather should be part of the variables considered in the ITS, naturally it is compulsory to have a good information management in this regard.

Incidentally, this is also the case for other non considered sources of non-recurrent congestion such as special events. Currently there is no data available pertaining to this cause and it may be originating delays that are not recognized and therefore no measures are neither thought nor undertaken. With no information about this item, is not possible to measure the share that it has on the overview of total delays.

## **6.4 Recurrent Congestion**

As it was mentioned in chapter 5, it was found that there are some motorway sections that have delays most of the time, that is, recurrent congestion. In other words, they are infrastructure bottlenecks, and they were listed on Table 5.2. These places then require to be checked closely, to identify the reasons why congestion is present there. For instance, the A13 in both directions present recurrent congestion, especially in the evening peak (after 16 h). In this particular case it may decrease when the A4 is finished in the section between Deft and Rotterdam.

Another example can be the junction between the A13 and the A20. Both motorways have recurrent congestion in the surrounding area of the intersection, either in the morning peak or in the evening peak, depending on the direction of the road.

These are examples of one of the uses that could have the methodology design: it can determine infrastructure bottlenecks, and assess the recurrent congestion that they cause. Clearly these infrastructure constraints are site-specific (e.g. curves, merging zones, weaving sections) and therefore it is not easy to extrapolate the results and propose some nation-wide measures. As it was presented in section

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3.2.1, the current policy in the Netherlands includes building extra capacity in the existing bottleneck areas. Consequently, it is considered that the developed methodology is a suitable tool to prioritize the investment of resources in this item, finding the places with the biggest problems of recurrent congestion i.e. infrastructure bottlenecks, in time (duration) and space (length of the zone affected).

## 6.5 The Nine-Step Process of Traffic Management

As it was mentioned in section 3.2.1, the Handbook Sustainable Traffic Management (RWS, 2003) explains the way to develop a new Traffic Management measure, within the reference framework of the Dutch policy. It is made in a nine-step process, shown in Figure 3.2. Therefore the above proposed traffic management measures should be referenced to this nine-step process. As they need to be referred to a particular location(s), naturally it was selected the case study area. It has to be noticed that they are an initial propose, that require to be evolved, and adjusted in case of be implemented. The nine steps are:

1. Initiate the Project: The main aim to accomplish is to decrease the negative impacts (delays) of non-recurrent events. In this step it is supposed that a reference time framework (e.g. during peak hours) for the measures should be defined. Taking into consideration that the non-recurrent occurrences may happen in any period of the day, therefore is not possible to define such time period. As it was mentioned above, the working area is that of the case study (see Figure 5.1).
2. Define the Common General Objectives: In the study area it was noticed that the A20 and the A13 are the most incident prone. Therefore the main objective is to decrease the delays they cause. Among the general objectives are to diminish the impacts of adverse weather conditions and roadworks as well.
3. Develop the Control Strategy: The most important flows in the region analyzed are those between The Hague and Rotterdam. Therefore the main concern is to maintain the relationship (connection) between these two cities. The available network resources to do so are two routes: the A20 and the A12 (via Gouda), or the A20 and the A13 (via Delft). The shortest route is the A20 and the A13, and therefore it has the priority. However this route experience the highest congestion levels.
4. Define the Frame of Reference: The criteria that would be used are 5 min aggregation period space mean speed (using Equation 4.2) and queue length. The threshold values are those used in the Netherlands to define the onset of congestion: 2 km for queue length and 50 km/h for speed. As it was mentioned in the previous step that the most important parts in the considered network are the

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A13 and the A20, then the inductor loop sensors in the intersection zone are used as the reference.

5. Describe the Actual Situation: The measurements of the threshold values should be done online, as the intention is to cope with non-recurrent events when they occur. Hence, the detectors in the mentioned zone (intersection between A13 and A20) should be monitored, to detect space mean speed and queue length values below the thresholds.
6. Identify and Analyze the Bottlenecks: In the case of the analyzed network, they were identified in the case study. In case these measures would like to be used in other parts of the motorway network, the methodology developed in this study gives a clear insight of the (infrastructure) bottlenecks location.
7. Develop the Services: Based on the traffic flows at the incident moment, look at the possible alternative routes and assess the impact of diverting traffic flows to them. In the network context used, in case of the A20 – A13 corridor between Rotterdam and The Hague present non-recurrent congestion (and indicator values mentioned below the threshold), look the impact of diverting part of the traffic flow to the A20-A12 corridor. This has to be done observing the flows and speed in the second corridor, at the moment of the occurrence.
8. Define the Measures: It is proposed that the executive control centers of the IM measures (see Figure 3.5) make an additional step. Besides dispatching surveillance, and informing RWS and ANWB, they should also inform to the traffic management control center, which has the capacity to determine the potential impacts of diverting flow to the alternative routes. They design the measures and the specific plan that should be deployed to tackle non-recurrent congestion that reaches the indicator threshold values.
9. Complete the Sustainable Traffic Management Project: This step involves integrating all the intermediate steps in a final document. Therefore no further comments are required.

## 6.6 Conclusions

After obtaining the results of the case study, the next step in the work was to propose some measures that intend to tackle different components of congestion indicated in this report: non-recurrent congestion and recurrent congestion.

In chapter 3 it was made a review of the current policies and measures that currently exist in the Netherlands, as well as in other countries in Europe. Naturally the recommendations given in this chapter were based on them. In the mentioned review, it was noticed that Dutch

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road authorities has made big efforts and invest money and efforts to develop to measures that currently exists. In the ex-post analysis made of this policies showed in the review, it was presented that they already decrease congestion levels even more than five percentage points, which is considered a significant change. For that reason, the measures proposed for incidents were focused on encourage the existing programs. For instance, based on the experience of the United Kingdom, it was proposed to include some traffic management (ITS) services within the measures that cope with non-recurrent congestion (IM and roadworks). To do so, it was used the nine-step process of traffic management in the Netherlands, as a reference frame. The proposed ITS measures include not only traffic management plans but also more active use of the information (e.g. VMS and information service providers).

Besides that, it is considered also practical to make some efforts in prevention field. In this way it is avoid that the occurrences happen, without having their undesirable effects. These efforts can be directed for instance to prevent speeding in the roads or promoting maintenance programs that avoid vehicles breakdowns

Perhaps the occurrence studied in this report that has the lowest level of development is adverse weather conditions. There was recommended (again) to improve the information system, which is the base to evaluate the current situation and supports the decision make process. It is also advisable that the ITS may include them as a part of the management of traffic system.

In this chapter was solved the research objective number 6: policy recommendations were made to mitigate the adverse effects of the non-recurrent congestion. This is the last of the research question stated in the first chapter and therefore the final part of this research can be undertaken: final conclusions and recommendations. This is the next chapter.

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# 7. Conclusions and Recommendations

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This is the final chapter of the research report and it includes the conclusions and recommendations derived from the study. These are the result of the entire process. The outline of the chapter is following the research sub-question, summarizing their answers found throughout the report. The next part is focused on outlining the way in which the main research objective was handled in this study and the solution given to it. Obviously these two parts are correlated. The last part is dedicated to further recommendations that arose in the development of this work finding.

## 7.1 Research sub-questions results

In this section the research sub-question are retaken, in order to highlight and summarize the answers given to them:

1. **How to match in time and space the information of the different data sources e.g. accidents (time and location) with congestion occurred?**

The inputs of this work included diverse databases that contain information of flows, speeds, and non-recurrent occurrences. These data make a distinction between locations in the motorways, and time (date, time of the day). Therefore they need to be matched in order to observe the causes of congestion (recurrent and non-recurrent) and their consequences.

This matching process of information between causes of non-recurring congestion events and resulting delays was done in the development of the proposed methodology, specifically in step 9. It was explained there that the non-recurrent delays obtained in step 7, could be explained as a consequence of the occurrence of one (or more) non-recurrent event contained in the databases analyzed in step 8.

2. **Design a method to identify quantitatively the different parts of the congestion and apply it to a case study.**

This is basically the work done in chapter 4. It is a fifteen-steps methodology, which is summarized as follows:

1. Define area (motorways) and time to be studied
2. Obtain the basic data:  $q$  and  $u$
3. Correct the input data (filtering)
4. Select the segments with recurrent congestion
5. In the step 4 segments, calculate recurrent delays

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6. Compute total delays
  7. Obtain non-recurrent delays
  8. Compare non-recurrent delays with non-recurrent occurrences in the databases.
  9. Determine if non-recurrent delays found in step 8 could be explained as a consequence of the occurrence of one (or more) non-recurrent event contained in the databases.
  10. Determine the extension in time and space of non-recurrent congestion
  11. Check if network effects are causing these non-recurrent congestion that cannot be explained as a consequence of a non-recurrent event (within the databases)
  12. Network effects are present when either a greater inflow or queues spilling back originated in congestion exist in the links upstream connected to that one under study
  13. The non-recurrent congestion that is not classified in the two above-mentioned categories, is then classified as 'other causes'.
  14. Report the results: delay decomposition

**3. How is diverted the traffic flow in the network when the non-recurrent elements are present?**

The answer to this research question was done in steps 12 and 13 of the methodology. In section 2.4 it was mentioned that the method used to describe network flows would be split fractions at nodes. Therefore in the methodology it was checked if the inflow at the node in the studied motorway is increasing as a result of a bottleneck in the neighborhood of the node, in the intersecting motorway. Then the effects may be either queues spilling back into the studied motorway and/or diverted inflow to the motorway link under analysis. As the methodology is designed to include several motorways, this network effects are looked for in the motorways that belongs to the study area and have intersection with the motorway under study.

**4. Which percentage of the total delays is produced by non-recurrent causes?**

Comparing the results obtained in the case study with those in Figure 1.2, it is clear that recurrent congestion has the biggest share in total delays, although in the case study the share was lower than the value presented in the problem definition. Naturally it was compensated with an increase in the share of non-recurrent delays, that in the problem definition had less than 20% of the total and the case study was more than 35%.

The results of the case study and the figure presented in the problem definition are comparable for the impacts of adverse weather conditions, with a percentage less than 1% of the total delays, and among the non-recurrent causes of congestion, incidents had the biggest percentage. Naturally this methodology is the base

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to make the more accurate the results presented in Figure 1.2, but still is necessary more information that includes the whole country to make a better assessment of the accuracy and compare of the results presented there.

**5. What is causing most of the non-recurrent congestion and how they could be tackled?**

In the case study it was found that most of the delays are caused by incidents. Nevertheless, they are also the most frequent occurrence between the causes studied, and thus is expected that they have the largest share in the total. In spite of that, it was found that even though only one place with roadworks were included in the study area, they still have a large share in the results of non-recurrent delays. Once again, it is consider necessary to apply the methodology to a broader dataset (in time and locations) to have a better overview, for instance in the Randstad area or even in the whole country, in other months and seasons.

**6. Make policy recommendations to mitigate the adverse effects of the non-recurrent congestion.**

It was noticed that Dutch road authorities has made large efforts and invest lots of money and efforts to develop to measures that currently exists. In the ex-post analysis of this policies showed in the review, it was presented that they already decrease congestion levels more than five percentage points, which is considered a significant change.

For that reason, the measures proposed for incidents were focused on encourage the existing programs. It was proposed to include some traffic management (ITS) services within the measures that cope with non-recurrent congestion (IM and roadworks). To do so, it was used the nine-step process of traffic management in the Netherlands, as a reference frame. The proposed ITS measures include not only traffic management plans but also more active use of the information (e.g. VMS and information service providers

Besides that, it is considered also practical to make some efforts in prevention field. In this way it is avoid that the occurrences happen, without having their undesirable effects. These efforts can be directed for instance to prevent speeding in the roads or promoting maintenance programs that avoid vehicles breakdowns.

Perhaps the occurrence studied in this report that has the lowest level of development in measures undertaken is adverse weather conditions. It is advisable that the ITS may include them as a part of the management of traffic system.

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## 7.2 Main research question outline

The main research question of this study is:

**“Which part of single event delays on the Dutch motorways is caused by the following non-recurrent elements: roadworks, incidents, and adverse weather conditions?”**

In the results of the case study it was observed that in general, recurrent congestion accounts for about 55% of the total. Thus non-recurrent congestion (with either known or unknown cause) has a share close to 45%. About 10% of the total delays was not determined the cause and they were classified as other causes and roadworks, incidents and adverse weather conditions the remaining 35%. Taking this part, it was found that the effect of the adverse weather conditions portion is negligible, with less than 1% of the total. The roadworks account for about 35% and the biggest share belong to incidents that have about 65%.

It has to take into account that these results of the non-recurrent congestion caused by roadworks, incidents and adverse weather conditions are indeed *extra* congestion. Often these occurrences were found within recurrent congestion zone. Therefore the results reported are extra congestion intensity (i.e. greater delay value) as well as extra congestion length, further than recurrent congestion zone.

## 7.3 General Conclusions

The first part of this study includes the literature review. It includes the theoretical background as well as available methods to solve the problem stated here. During this review it was noticed some gaps in the assessment of non-recurrent congestion, listed below:

- Explicit assessment of multiple (more than one) causes at once
- Possibility to include in the model unconsidered causes
- Lack of a structured methodology
- Broad estimations based on year dataset.
- Lack of considering network effects

Therefore the methodology was developed to fill these gaps.

The next part of the study comprises review of existing policies and measures to deal with non-recurrent congestion. There could be seen that in the current practice in the Netherlands, there are implemented various strategies to deal with roadworks and incidents as causes of non-recurrent congestion. Therefore their impact on the traffic operations is already lower than the situation with no plan implemented. Nonetheless, there is not a clear measure intended to deal with adverse weather conditions.

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In the reviews (literature and policy) made, it was gathered the information required to propose a new methodology to assess non-recurrent congestion. This was naturally the next step and was summarized already above. It has to be mentioned that originally one of the main research objectives was to develop a methodology. Nonetheless among the original objectives it was not included to develop a computer tool, and therefore this is an additional achievement in the process.

The methodology was applied to a situation with real data, to corroborate that it works properly. It was found that the delay results obtained applying the methodology are reliable, as they properly reproduce field conditions. Hence, it was validated the designed methodology, as it works correctly. It is especially noticeable matching incidents locations (in time and space) with resulting congestion.

The next step was to apply the validated methodology to a case study with real data in order to obtain results and analyze them. This first thing noticed in the results obtained applying the methodology tend to be scattered. In most of the average calculations, it was found that the standard deviation was larger than the mean values. This is the consequence of compare extreme values (high and low). It was also noticed that although only one place presented roadworks in the study area, their outcomes are significant in the non-recurrent delays.

The methodology also gives the locations and daytime in which usually congestion is observed, namely recurrent congestion locations (in time and space). Most likely road users and authorities are aware of these locations, but probably the delays that are facing road users are not measured. The methodology provides hard data about locations, daytime, intensity and duration of recurrent congestion, which could be even used in other applications.

It was found in the results of non-recurrent delays classified as 'other causes' are higher than expected. It was shown that part of them are originated in bottlenecks whose cause is not among the databases. Therefore it is considered that although the quality of the existing information is high, it is still necessary more information about different kinds of occurrences, different from those considered in this study. Other part is caused by spillback effects initiated at recurrent delays zones and other start at spillback effects, originated outside of the study area, and failures in the sensor measurements.

Among the causes of non-recurrent congestion, the results obtained for adverse weather congestion were marginal in the measurement period, contrary to the expected. The share in the total results is less than 1%.

The general picture of the delays obtained is similar to that one presented in the problem definition, as expected. That is, the share of the different parts of delays are similar to that presented in the problem definition, which was built using a correlation method (inaccurate).

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Naturally they are measuring the same variables, and then the results should be similar.

In the sensitivity analysis it was found that methodology results more sensitive to changes in reference speed than in percentage of days with congestion. In the same manner as traffic modeling programs, where the input values should be chosen using the criterion and expertise of the user, the selection of the input parameters in the algorithm designed should be carefully done, especially the reference speed. It is considered that the initial reference speed value of 80 km/h is adequate, and thus is recommended to use it in future applications. With regard to percentage of days with congestion, based on the results of the sensitivity analysis, it is considered that 50% or 40% are suitable values.

Comparing the results of the average delay caused by incidents computed in the case study with those reported in the literature, it was noticed that they are in the same magnitude order. Furthermore there were found higher average delay values as well as lower. It is considered that no extreme values were found, indicating that the results are reasonable.

After obtaining the results of the case study, the next step in the work was to propose some measures that intend to tackle different components of congestion indicated in this report: non-recurrent congestion and recurrent congestion. It was noticed that Dutch road authorities has made big efforts and invest money and efforts to develop to measures that currently exists. For that reason, the measures proposed for incidents were focused on encourage the existing programs. Thus, it was proposed to integrate the ITS services on the IM plans. There are two different approaches of ITS in the IM services. The first is related to traffic management measures, where based on the traffic flows at the incident moment, look at the possible alternative routes and assess the impact of diverting traffic flows to them. Based on this, design a response plans to decrease the potential delays. The second approach involves provide information to road users by means of VMS signs, as well as information service providers.

Perhaps the occurrence studied in this report that has the lowest level of development is adverse weather conditions. There was recommended (again) to improve the information system, which is the base to evaluate the current situation and supports the decision make process. It is also advisable that the ITS may include them as a part of the management of traffic system.

## **7.4 General Recommendations**

One of the main problems found during this work, was the fact that the weather database as such is not available. It hinders the whole process of computing non-recurring delays. Thus is highly

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recommended to build this database, which is considered not a very complex task, taking into consideration the information already available. Besides that, this database includes only rain and there are other sources that need to be included in the future such as snow or fog.

Nowadays meteorology is an advanced science that has developed their knowledge in forecast weather conditions. This knowledge has big potential to be included on ITS services, but this big knowledge is wasted. Thus the main advice in this direction is regarding to include this forecast on the different types of ITS, such as on-board devices, VMS panels, et cetera. Likewise way that ITS works for decrease non-recurrent congestion caused by incidents and roadworks, it could also work for adverse weather conditions, increasing their benefits. ITS giving advice regarding adverse weather conditions could have an effect on choices such as departure time, mode, and destination, among many others. It could even made that people cancel those trips that are not essential due to delays caused by adverse weather conditions.

It was observed that there is a significant part of the delays that cannot be explained as a result of lack of information. In the case study there were detected some bottlenecks that cannot be explained as a result of the non-recurrent occurrences within databases. Therefore, it is necessary to have more information on this field to make more accurate this process. For instance, in the literature review it was presented that there is an additional cause of congestion that has no information available in the Netherlands: special events. It may also be contributing to this effect.

The last recommendation is regarding to it is necessary to have more data. It means apply the developed methodology in other parts of the country, with a broader timeframe. As it may be expected the more information available the more accurate the conclusions.

Applying the methodology in the case study, it was noticed some shortcoming in it. For instance, the methodology considers one single value of reference speed, for all the motorways stretches in the analysis period. This fix value makes the methodology less robust, as it cannot cope with changes in some parts of the network. For future research it is recommended to look for a technique that lets introduce different reference speed values for different parts of the network (or motorways sections).

The way in which the methodology handles incidents is considered another weak point. As they are included all in the same database (IM), it does not differentiate among the severity of the occurrence (e.g. number of lanes blocked). Therefore the outcome delays are scatter with large standard deviation values, close to the mean values. In order to diminish this effect, it is proposed to explore the option of classify beforehand the incidents in the IM database, according to the severity

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of the occurrence: e.g. number of lanes blocked, duration of the blockages, et cetera. Based on these criteria the database could be split, and hence the input would be several incident databases instead of one large.

It was noticed during the algorithm validation some discontinuities in the measurements of the inductor loops detectors, which led to wrongly classify some part of the delay. Therefore the algorithm is sensitive to these discontinuities. This is considered that the filtering process should prevent it to happen. Consequently it is recommended to develop a project that incorporates the filters in the data retrieving process from Monica database (Monigraph interface).

Besides that, there were also some shortcomings noticed in the developed computer tool. It has to be taking into account that it is its first development, and then there are many details that could be improved. For instance the data aggregation process is not integrated yet to the main core of the tool. It has another problem obtaining the final cause of congestion in the case of network effects, which had to be done 'manually' as the process is not automated yet. Thus it is considered that the new releases of the computer tool should try to find a way to improve the routines to reduce the computation time, the user interface in order to make it more user friendly, and automate the procedures of compute the results and obtain the final cause of network effects.

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# Appendix A: Results set for the A4 and the A16

Figure A.1: Total delay A4. Left and Right direction per period of the day

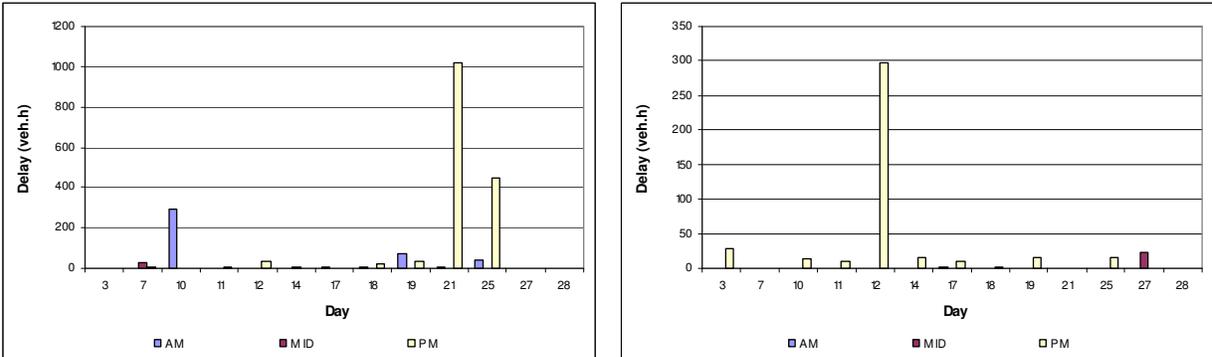


Figure A.2: Delay decomposition for the A4. Left and Right direction

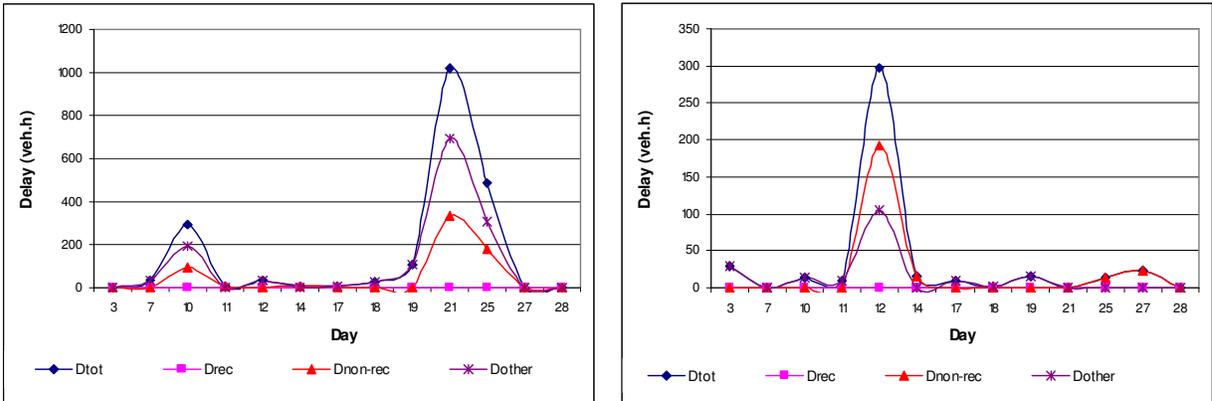


Figure A.3: Share of different factors in total Delays for the A4. Left and Right direction

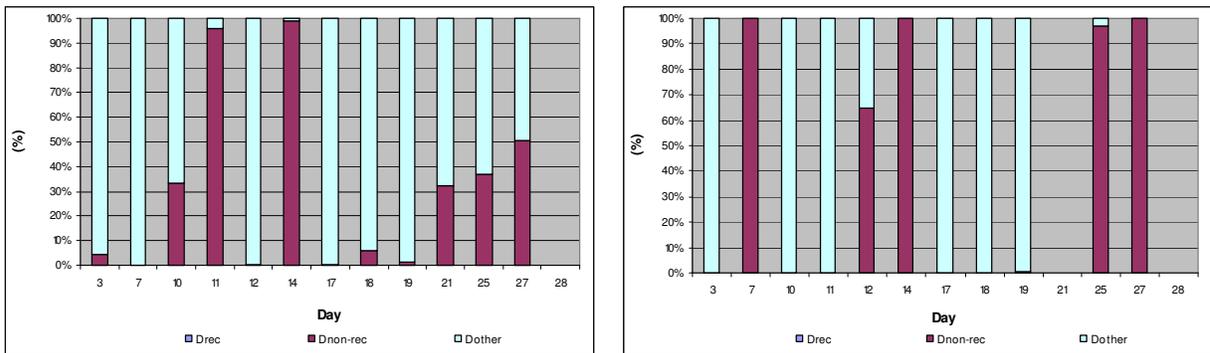


Figure A.4: Total delay A16. Left and Right direction per period of the day

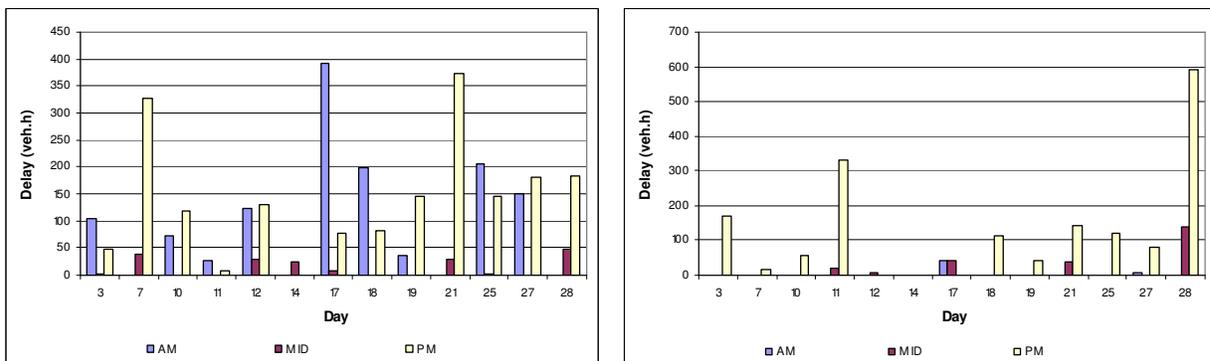


Figure A.5: Delay decomposition for the A16. Left and Right direction

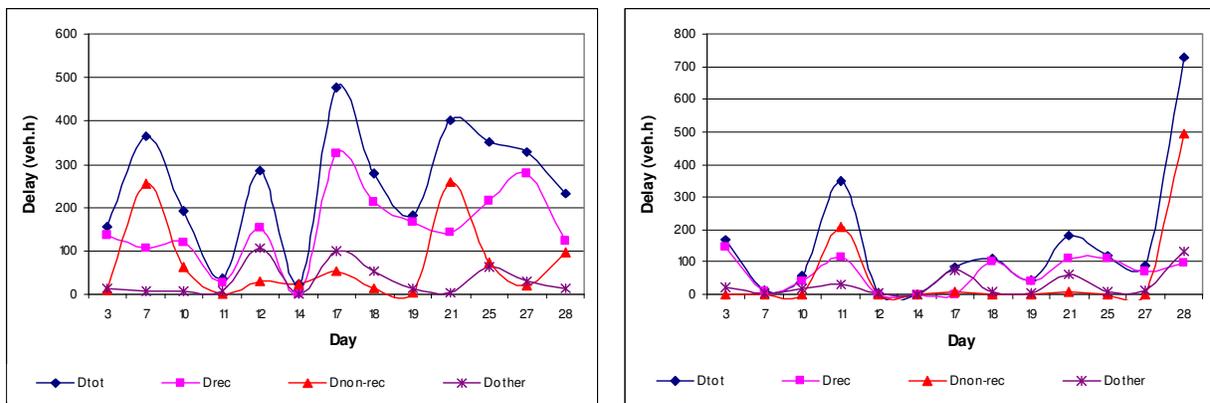
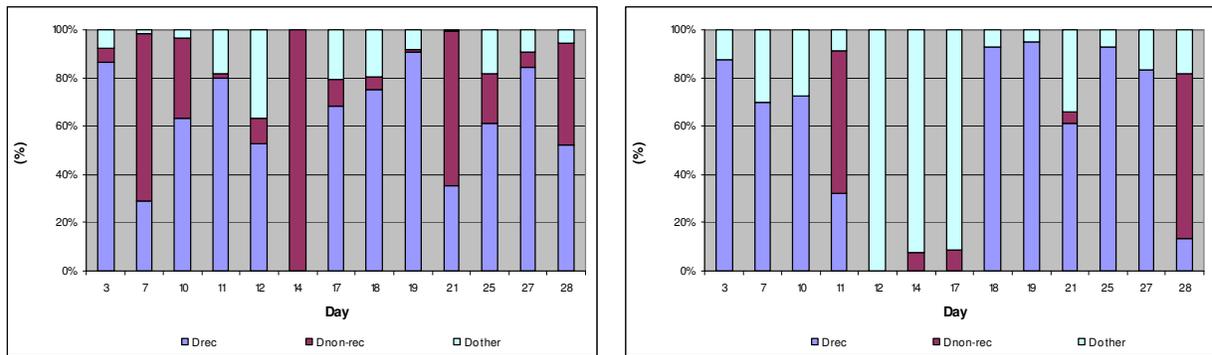


Figure A.6: Share of different factors in total Delays for the A16. Left and Right direction



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## Appendix B: Computer tool user guide

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As it was mentioned in section 4.4, a computer tool was developed in Matlab in order to automate the steps mentioned in the methodology. The general idea of this tool is to take the outputs of MoniGraph program, which are basically speeds and flows, process it together with the databases of the occurrences, to obtain the outcomes of the algorithm. This appendix is devoted to explain the computer tool interfaces with the user and the steps involved, to obtain the results. It has to be noticed that as the computer tool was created in Matlab environment, then it is expected that the user is familiar with it.

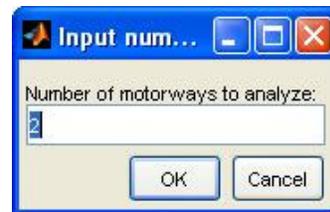
The name of the main function is `delay_decomposition.m`. The general inputs of the computer tool were presented in Figure 4.3. However, the only input parameter that has to be created in Matlab beforehand is the databases of non-recurrent occurrences (`nonrecurrent_database`), again as presented in Figure 4.3. The rest of the inputs mentioned in section 4.4 are captured in screens. The outcome is one Matlab structure (`Structure_name`) that contains all the information of the motorways included in the study area, which will be explained later on. Thus it has to be typed in Matlab:

```
Structure_name = delay_decomposition (nonrecurrent_database);
```

Then it appears a window asking about the number of motorways included in the study area (step 1 of the algorithm). This window is presented in Figure B.7.

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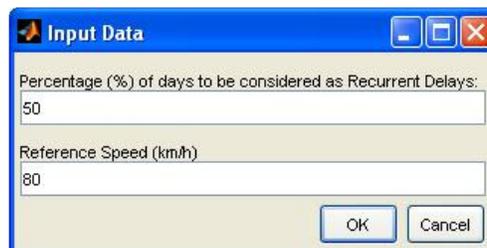
Figure B.7: Computer tool input window. Number of motorways



The next window asks for percentage of days considered as delays, and the reference speed, as presented in Figure B.8.

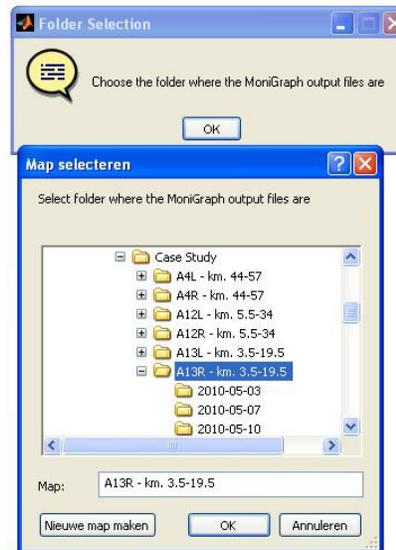
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Figure B.8: Computer tool input window. Percentage of days considered as delays, and the reference speed



Having defined the basic parameters, the next step is to find the Monigraph outputs, which are in folders. It has to be said that there is one folder per direction. This is also made in a window like the one shown in Figure B.9. It has to be made twice, one per direction, for each motorway in the study area.

Figure B.9: Computer tool input window. Folder selection



After capturing all the basic data, the computer tool follows the methodology steps and decomposes delays. The last windows displayed are the input of the network configuration (for the network effects analysis, steps 11 and 12 of the algorithm), which are basically two: whether or not exist an intersection between the motorways mentioned in the study area, and if it is the case, the hectometer in each motorway of the intersection. These windows are shown in Figure B.10 and Figure B.11.

Figure B.10: Computer tool input window. Network configuration

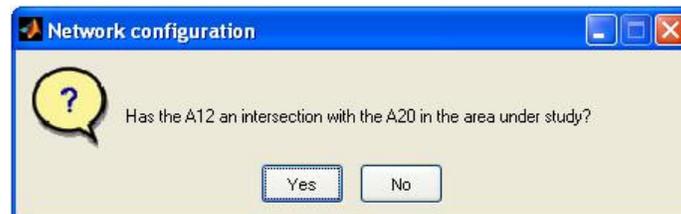
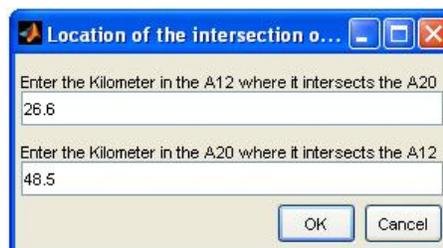


Figure B.11: Computer tool input window. Location of the intersections



After finishing the processing info for all the motorways considered in the study area, the outcome is a Matlab structure that contains one sub-structure for each motorway for each direction. For instance, in the

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case study there were 10 sub-structures, 5 motorways and 2 directions. Each one of these sub-structures have basically the 3D cubic matrices described in section 4.4 (one layer per day in the analysis period) with the following information: Speeds, Volumes, delays decomposition: total delay, recurrent delay, non-recurrent delay, other delay, and network effects delay. Besides that, there are other matrix that is related to the databases of non-recurrent occurrences, and are the delays obtained in each one of them.