Empirical Analysis of Real-time Traffic Information for Navigation and the Variable Speed Limit System

Williams Ackaah

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Gutachter/Gutachterin:

1. Univ.-Prof. Dr.-Ing Klaus Bogenberger,
   Universität der Bundeswehr München
2. Prof. Dr. Robert L. Bertini,
   University of South Florida, USA

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# Contents

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# Publications

Some ideas, figures, and tables presented in this dissertation have appeared previously in the publications listed below:

## Journal Papers

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- Gary Riggins, Robert L Bertini, **Williams Ackaah**, and Martin Margreiter. Evaluation of driver compliance to displayed variable advisory speed limit systems: Comparison between Germany and the U.S. *Transportation Research Procedia*, (15):640-651, 2016.

- **Williams Ackaah**, Gerhard Huber, Klaus Bogenberger, and Robert L Bertini. Assessing the harmonization potential of variable speed limit systems. *Transportation Research Record: Journal of the Transportation Research Board*, (2554):129-138, 2016.

- Gary Riggins, Robert L Bertini, **Williams Ackaah**, and Klaus

Bogenberger. Measurement and assessment of driver compliance with variable speed limit systems: Comparison of the U.S. and Germany. *Transportation Research Record: Journal of the Transportation Research Board*, (2554):77-88, 2016.

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- Gary Riggins, Robert L Bertini, **Williams Ackaah**, and Martin Margreiter. Evaluation of driver compliance to displayed variable advisory speed limit systems: Comparison between Germany and the U.S. In *International Symposium on Enhancing Highway Performance (ISEHP) Compendium of Papers, Berlin, Germany*, 2016.
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- **Williams Ackaah**, Gerhard Huber, Klaus Bogenberger, and Robert L Bertini. Assessing the harmonization potential of variable speed limit systems. In *Transportation Research Board 95th Annual Meeting Compendium of Papers, Washington DC*, 2016.
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variable speed limit systems: Comparison of the U.S. and Germany. In *Transportation Research Board 95th Annual Meeting Compendium of Papers, Washington DC*, 2016.

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# Zusammenfassung

Erweiterte Reiseinformationssysteme (ATIS, aus dem Englischen „advanced traveler information systems“) stellen heutzutage einen der zentralen Ansätze zur Verkehrssteuerung dar. ATIS liefern Informationen über die vorherrschende Verkehrssituation, verkehrsrelevante Ereignisse und zu Wetterlagen, die sich nachteilig auf den Verkehr auswirken können. Diese Informationen werden über Medien wie das Radio, Fernsehen, Internet, Smartphone und mittels dynamischer Navigationssysteme verbreitet, sie können aber auch durch dynamische Streckenbeeinflussungsanlagen (VSL, aus dem Englischen „variable speed limit systems“) zur Verfügung gestellt werden. Das Kernziel dieser Dissertation war die Analyse, ob die durch VSL zur Verfügung gestellten Verkehrsinformationen in der Praxis mit den durch Echtzeit-Verkehrsinformationen (RTTI, aus dem Englischen „real-time traffic information“) zur Verfügung gestellten Informationen übereinstimmen.

Um diese Analyse überhaupt zu ermöglichen, wurden zunächst Methoden zur Evaluierung verschiedener VSL Systeme entwickelt. Grundlage dieser Ansätze war die Erwartungshaltung, dass VSL Systeme Vorfälle zunächst zu erkennen haben, um anschließend, durch visuelle Warnhinweise oder durch das Beschränken der erlaubten Höchstgeschwindigkeit, Unfälle zu verhindern, Verkehr zu harmonisieren und Verkehrsstörungen abzuschwächen. Entsprechend wurden Methoden entwickelt, welche bewerten, inwieweit ein VSL System in der Lage ist, Störungen im Verkehrsgeschehen zuverlässig zu erkennen, rechtzeitig vor Stauenden zu warnen und daneben eine Harmonisierung des Verkehrs sicherzustellen. Um die Fähigkeit Störungen zu erkennen bewerten zu können, wurde zunächst eine Verkehrslagerekonstruktion auf Basis von Induktionsschleifendetektoren durchgeführt. Die Rekonstruktion wurde anschließend räumlich und zeitlich diskretisiert und mit den vom VSL System angezeigten Geschwindigkeitsbegrenzungen verglichen. Die Fähigkeit vor Stauenden zu warnen wurde mit Hilfe virtueller Fahrzeugtrajektorien

bewertet. Konkret wurde geprüft, ob ein Fahrer durch das betrachtete VSL System angemessen vor Stauenden gewarnt worden wäre oder nicht. Zu diesem Zwecke wurde zwischen verschiedenen Szenarien, die ein Fahrer erfahren kann, unterschieden. Die Szenarien wurden vorwiegend durch den räumlichen Abstand zwischen der durch das VSL System angezeigten Stauwarnung und dem stromaufwärtigen Ende des vorausliegenden Verkehrsstaus charakterisiert. Schlussendlich wurde ein Verfahren zur Bewertung vorgestellt und verwendet, welches eine objektive Bewertung der Fähigkeit, Störungen zu erkennen und vor Stauenden zu warnen, ermöglicht. Darüber hinaus wurden zwei Ansätze zur Bewertung der Harmonisierungsfähigkeit eines VSL Systems eingeführt. Der Erste betrachtete, ob das VSL System in der Lage ist Inhomogenität im Verkehrsfluss zu reduzieren, der Zweite, ob die Folge angezeigter Geschwindigkeitsbegrenzungen konsistent ist. Der Grad an Inhomogenität wurde anhand von Geschwindigkeitsunterschieden, die entlang des Verkehrsflusses auftreten, gemessen. Allerdings konzentrierte man sich bei diesen Messungen auf sogenannte „metastabile“ Verkehrszustände (d.h. der Verkehrsfluss überschreitet einen gewissen Grenzwert, aber die vorherrschenden Geschwindigkeiten sind höher als bei einem Verkehrsstau). Die Konsistenz der Anzeigen des VSL Systems wurde bewertet, indem die Folge angezeigter Geschwindigkeitsbegrenzungen, die von Fahrern erlebt worden wären, betrachtet wurde. Um dies zu ermöglichen, wurde zunächst die Verkehrslage rekonstruiert. Diese Rekonstruktion wurde wiederum zur Ableitung virtueller Fahrzeugtrajektorien verwendet, die es schließlich möglich machten, den Weg eines einzelnen Fahrers und die Folge an Geschwindigkeitsbegrenzungen, die er erlebt hätte, wenn er zu einem bestimmten Zeitpunkt den betrachteten Streckenabschnitt passiert hätte, zu reproduzieren.

Im zweiten Schritt wurde dann zunächst ein qualitativer Vergleich zwischen VSL und RTTI vorgenommen. Ziel dabei war es Einblicke in die Merkmale der beiden Informationssysteme zu erhalten und diese besser zu verstehen. Zu diesem Zweck wurden berechnete Verkehrslagedarstellungen abermals diskretisiert und die hieraus resultierenden „realen“ Geschwindigkeitswerte den vom VSL System angezeigten Geschwindigkeitsbegrenzungen gegenübergestellt. Die Diskretisierung stellte dabei sicher, dass die beschränkte Raum-Zeit-Auflösung, der VSL Systeme und RTTI typischerweise unterliegen, innerhalb des Bewertungsprozesses berücksichtigt wurde. Auf ähnliche Weise wurden die RTTI mit den realen Geschwindigkeitswerten abgeglichen. Allerdings wurde ein Pufferbereich hierbei eingeführt. Die dahinterstehende Idee war es, dass Staumeldungen, die stromaufwärts des eigentlichen Staueregnisses auftreten, die also einen Stau melden wo gar kein Stau zu finden ist, nicht zwingend als Fehlmeldungen interpretiert werden müssen. Stattdessen können solche Meldungen als Warnhinweise vor nahenden Stauenden interpretiert werden und können somit ihrerseits zur Erhöhung der Verkehrssicherheit beitragen.

Um ihre Anwendbarkeit zu gewährleisten, wurden die innerhalb dieser Arbeit entwickelten Methoden auf Realdaten angewandt. Als Teststrecke diente die Autobahn A99 in der Nähe Münchens in Deutschland.

# Abstract

Advanced traveler information system (ATIS) has been used and is viewed as an essential component for present-day traffic management. ATIS may provide information such as the traffic situation, incidents, and weather conditions which may adversely affect traffic. This information may be disseminated through media such as radio, television, internet, mobile phone, dynamic navigation device, and the variable speed limit (VSL) system. The main objective of this dissertation was to examine whether traffic information, provided by VSL systems and real-time traffic information (RTTI) for navigation systems, are consistent with each other.

Before the comparative analysis, methods for evaluating different features of VSL systems were developed. A VSL system is expected to detect incidents and take measures to avoid crashes, postpone, or alleviate congestion by providing advance warning messages and/or harmonize traffic by reducing speed differences between vehicles. Methods for assessing three features of VSL systems, namely, incident detection, warning, and harmonization efficiency are presented. For the purpose of evaluating incident detection, the traffic state was reconstructed from dual loop detector data, discretized, and compared with the message signs of the VSL. Warning efficiency was assessed by generating virtual vehicle trajectories and determining whether a driver experienced adequate warning. Scenarios for message signs and their influence on traffic safety were identified according to the distance of the warning from the tail of the congestion. Weightings for detections and missed detections based on the different scenarios were developed. A quality evaluation method was then used to grade the levels of the system in their incident detection and warning efficiency. Two approaches, based on the ability of the system to reduce inhomogeneity in the traffic stream and improve the consistency (proper coordination) of the displayed speed limits were proposed for harmonization assessment. Inhomogeneity in the traffic stream was checked by identifying the traffic state and assessing the ability of the system to reduce the speed differential in the metastable traffic state (i.e., flows > free flow, but with speeds > congestion speed). The coefficient of variation (CV) was employed to quantify the standard deviation of speed. Consistency was assessed by observing the consecutive dynamic changes in the displayed speed limits as drivers traverse the route. This was done by reconstructing the traffic state, generating virtual trajectories based on the reconstruction, and finally tracking the virtual vehicles to reproduce the sequence of speed limits that drivers would have experienced.

For the comparison between VSL and RTTI, firstly, a qualitative analysis was done to understand and provide insight into the characteristics of the two information sources. The evaluation was made by obtaining the differences in speeds between the discretized space-time representation of reality and the space-time traffic information displayed by the VSL/RTTI. The discretization ensured that the method takes into accounts, limitations faced by the providers in broadcasting the information. The quantitative comparative analysis was also made by superimposing the space-time areas of reality to the space-time areas of the information broadcast. However, a predictive buffer was introduced in the assessment. The predictive buffer was considered as areas of traffic information which could be considered as advance warning messages, or rightly predicting and giving congestion information prior to the onset of actual congestion, which otherwise would have been taken as false alarm. This was motivated by the fact that optimal control approaches include the prediction of congestion in their control strategies.

The methods developed in this research work have been applied to real world problem to prove its applicability. The site for the case study was the autobahn A99, near Munich, Germany.

# Chapter 1

# Introduction

## 1.1 Background

Growth in traffic demand has resulted in traffic congestion during certain time periods on most categories of road networks. In the industrialized countries such as Germany, congestion on freeways[1] is, nowadays, a commonplace. Congestion may occur when there are more vehicles than the road can accommodate (demand > supply). It may also be caused by a bottleneck (e.g., merging or weaving areas, on-ramps, road traffic crashes[2], and construction works) on a section of the roadway. The traffic hold up at a bottleneck typically originates from the phenomenon that the maximum achievable outflow from a traffic jam created at the location is often lower than the capacity of the road, termed, capacity drop [1]. Congestion is undesirable and may cause delay, environmental pollution, noise and even frustrate motorists and commuters which also have health implications. It may also lead to road traffic crashes and degradation of the road infrastructure. The center for economics and business research (Cebr) studied the cost of congestion in four advanced economies, that is, Germany, Britain, France, and the United States of America (USA) [2]. The study revealed that road users spend, on average, 36 hours in congestion every year in metropolitan areas. The

[1]Freeways and motorways are controlled access highways that are intended to provide uninterrupted, fast moving traffic. Motorway is used, mostly, in the United Kingdom (UK) and other countries. Throughout this dissertation, the term "freeway" is used for roads with limited access.

[2]Safety activists advocate for the use of the word "crash" instead of "accident." They argue that the term accident connotes occurrence which results from unintentional and natural causes. Therefore, it cannot be prevented. However, road traffic collisions can be avoided with adequate resources invested in appropriate preventive measures.

total economy-wide cost across all four advanced economies was estimated to be $200.7 billion in 2013 and is expected to rise to $293.1 billion by 2030.

Whereas congestion caused by bottlenecks can be resolved by simply removing the bottleneck, congestion resulting from capacity problem are more challenging to resolve. Traditional attempts to deal with the issue have focused on building new roads and expanding existing ones. Meanwhile, the ceaseless increase in demand for mobility has also meant that traffic keeps on increasing. Space and financial constraints make it practically impossible to continually expand the road infrastructure to accommodate the increasing traffic demand, and it is now not considered as a viable option. Expansion of existing or construction of new roads does not have only financial burden on the government, but also social impact on the community. Displacement and resettlement of the affected residents, relocation of businesses and community services (e.g., parks and churches) may have social and psychological impacts due to the disruption of social relationship, and establishing relationships in a new social environment [3]. Studies have established that road expansions spur new travel, known as induced demand, and thus may fail to relieve traffic congestion [4–8]. Therefore, a more pragmatic and proactive means of managing the existing infrastructure has become necessary.

Freeway traffic control started in the nineteen sixties (1960s), albeit manual form of data gathering, fixed-timed or static controlled, but have undergone various forms of automation since then. The increasing complexity of traffic congestion and the continuous change of traffic characteristics such as flow and speeds in the space-time dimensions necessitated that dynamic methods are employed to solve the constantly varying traffic problem. One thing which has affected virtually every facet of our lives since its inception is information and communication technology (ICT). With the revolution in ICT since the 1990s, the pace in implementation of dynamic traffic management[3] (DTM) has gained momentum. Intelligent transport system (ITS) has provided an avenue and is viewed as an essential component for present-day traffic management. ITS is concerned with the application of electronic information and control in increasing safety and dealing with the growing emission and congestion problems. It may be based on information supplied within the vehicle or by traffic management centers and applied to the vehicle and user (e.g., navigation systems for real-time traffic information, cruise control, and collision avoidance systems), or integrated into

[3] Dynamic traffic management is also referred to as active traffic management (ATM) in literature.

the transportation infrastructure (e.g., variable speed limit systems). ITS has shaped new ways of managing and optimizing the use of the existing transportation infrastructure. An overview of some of these ITS control strategies, applied on urban arterial corridors and freeways, is given in the following.

### Ramp Metering

This is a freeway control strategy that uses signals to control the amount of on-ramp traffic that enters the main freeway. The signal, installed on the ramps, reduces the disruptions which would have been caused by the merging on-ramp traffic thereby increasing throughput on the freeway and reducing the chances of collisions as a result of the merging traffic. Different control strategies are in operation. Some systems use operators who monitor the traffic situation via closed-circuit television (CCTV) camera and activate or deactivate the meter. There are also systems which are semi-automated or fully automated. Ramp metering has been found to improve capacity, flow, speed, travel time, vehicular emissions, and air quality [9–13]

### Hard-shoulder Running

This freeway control measure temporarily creates an extra lane by allowing vehicles to use the hard shoulder. The aim is to increase the capacity of the freeway at busy times when capacity problems can result. Traffic control devices on the road side or put across the carriageway (overhead gantries) direct drivers to use the shoulder when it is permitted.

In some cases, the shoulder will be opened to only dedicated vehicles (e.g., public transport or high occupancy vehicles) to facilitate the faster movement of those vehicles. Again, monitoring of the traffic condition in order to switch on/off the use of the shoulder may be done through the use of CCTV or automatically. Positive impact of the effect of hard-shoulder running on capacity has been reported in several studies all over the world (e.g., [14–18])

### Reversible Lane

Under the reversible lane[4] control measure, a lane may carry traffic in one direction during part of the day and in the other direction during other part of the day to adapt to changing traffic conditions. It is useful when the traffic flow is not high in both directions simultaneously and therefore ensures efficient use of the road capacity. There is transition period (i.e., during the reverse process) when the lane to be reversed is closed temporally to both directions of traffic to clear vehicles using it to avoid any head-on collisions. Overhead traffic lights and sometimes lighted street signs communicate to drivers which lanes are open or closed. Movable center divider (median) has also been used to separate the different driving directions. The ability of reversible lanes to ameliorate congestion has been proven [19–21].

### Traveler Information or Real-time Traffic Information (RTTI)

RTTI presents traffic information to travelers to assist them in planning their journeys and also provide guidance when on the road. It is understood that providing travelers with better information will affect travel behavior and result in reduced travel time and congestion along with reduced pollution and energy consumption. RTTI is transmitted through various media. Examples of the mechanisms for RTTI are described below.

**Variable speed limit (VSL) systems**: VSL systems use dynamic speed limits to manage traffic depending on the prevailing traffic situation. Further to the speed limits, some VSL[5] systems may display message signs which provide warnings of hazardous conditions. Additional information such as constructional works, travel time, and route guidance may also be displayed by a VSL system. The VSL control device, which is mostly installed on overhead gantries across the carriageway, may also implement dynamic truck restrictions which require heavy goods vehicles not to overtake or use designated lanes during peak periods.

**Dynamic navigation systems**: In-vehicle or mounted navigation devices are

[4]Reversible lane is also referred to as tidal flow, particularly, in the United Kingdom.

[5]Variable speed limit systems, in one form or another, is used in literature with various names. Some of the names which have been used include dynamic speed limit (DSL) systems, dynamic message signs (DMS), changeable message signs (CMS), etc.

also used to provide motorists static or dynamic route guidance. Static route guidance is concerned with providing navigational assistance to motorists who may be unfamiliar with a road network. A geographical database of the road network and its characteristics such as speed limits, distances, and road class is required. Here, the traffic situation is not taken into consideration. Routing is mainly based on the shortest travel time path to the destination. Dynamic navigational systems, on the other hand, take into consideration, the traffic situation in deciding the minimal time route. Information on the prevailing traffic condition is updated in real-time. Dynamic route guidance system is seen as efficient way of managing network traffic.

**Radio and television broadcasts**: Traditionally, this has been the source of traffic information. The radio and television stations, after obtaining the traffic information from their sources, broadcast it to their listeners/viewers. For instance,

“Route A99; direction A towards B, congestion between landmarks C and D.”

The limitation of radio and television traffic information broadcast is that it is not available at all times [22, 23]. Again, radio and television based traffic information are limited in the frequency of broadcast and the exact spatial extent of traffic management information that they provide.

**Internet services**: RTTI is also presented to consumers on the internet. This may be in the form of congestion maps. An example is shown in Figure 1.1 for Munich, Germany. The website color codes segments according to the degree of travel time delay with links marked red indicating more delays than segments colored orange. The exact delay time and queue length could be obtained by pointing on the colored link. Information such as road closures and road works may also be illustrated on the map. The advantage of presenting traffic information on the internet is that it is highly effective and versatile [22, 23]. It is also relatively easy and cost-effective to maintain and update.

**Mobile phone services**: Traffic information consumers can subscribe to a service from a provider where they receive information in the form of short messaging service (SMS) alerts. Fast development in the mobile phone technology and wireless internet connectivity has also ensured that RTTI can be accessed via the internet or through a specially designed application downloaded onto the smart phone. Telephone information service has also been part of traffic information.

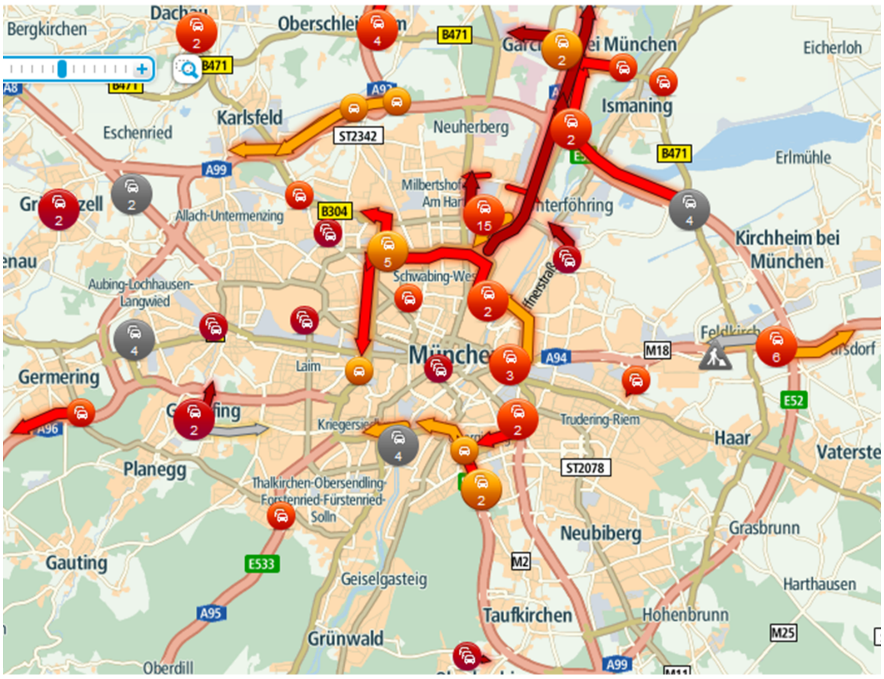



Figure 1.1: Real-time traffic information in Munich, Germany (Source: [24])

Under this circumstance, travelers call a center for real-time traveler information. The information is, mostly, automated. Callers could select a specific route or segment from the system's main menu to receive a current report on traffic conditions [22, 23, 25].

*ITS has changed the face of traffic management considerably. Automated, traffic-responsive management measures are preferred because of their ability to deal with the dynamic nature of the congestion problem. But, are there problems resulting from our dependence on artificial intelligence (AI) and their control theories? This dissertation focuses on VSL systems and RTTI. Real-time traffic information, in this context, refers to traffic information by dynamic navigation devices.*

## 1.2 Context and Problem Statement

VSL and RTTI provide information to motorists and commuters in real-time to assist them in planning their journeys and also provide guidance when on the road. These two mechanisms may come under the broader concept of advanced traveler information system (ATIS). ATIS may provide information such as the traffic situation (which may be in the form of queue length, travel time, or delay), incidents and their locations, events (e.g., road works, road closures, and demonstrations), optimal routes, and weather conditions which may adversely affect traffic. This information may be disseminated through the different media as discussed in section 1.1. ATIS may be provided by a private operator or from a public source. Consumers can subscribe for a fee, although there are many free sources also available.

Generally, ATIS may be categorized into two groups: pre-trip and en-route. Pre-trip ATIS (e.g., internet services, radio, and television broadcast) may provide travelers with real-time traffic information to enable them to decide their departure time, route, mode, and destination prior to the trip. En-route ATIS (e.g., VSLs and dynamic navigation systems) provides real-time information to aid drivers make informed decisions when on the road. Whereas pre-trip ATIS may have effect on the entire road network, en-route systems such as VSL may be intended as a link control strategy. It is understood that providing travelers with better information will affect travel behavior and result in reduced travel time and congestion along with reduced pollution and energy consumption [26–30]. Many studies (e.g., [26, 29–37]) have found considerable improvements in network performance through the provision of ATIS at various levels of market penetration. The benefits of ATIS to users are not only in terms of time and monetary savings, but also emotional and psychological well-being as it removes uncertainty and anxiety [29, 38]. However, the success of ATIS depends on, among other factors, whether drivers consider it useful and their response to the provided information [38, 39]. **Accuracy**, **timeliness**, and **reliability** of the information provided are very important for consumer confidence and subsequently, boosting positive response. For private ATIS providers, poor quality information will have a terrible consequence on their businesses. Studies have established that travellers will not pay or use information unless they perceive it to be reliable and timely [38–41]. When accuracy drops below a critical point, one is better off not using ATIS and relying on experience with historical traffic patterns [42]. The question then arises:

*what is the quality of traffic information being broadcast on our roads?*

There are, currently, many market players in the traffic information industry producing traffic reports for consumers. This information from different sources could be on the same incident. Kattan, et al. [43] established a correlation between drivers who seek traffic information from different sources and their compliance level. The study found that drivers who listen to radio traffic information or watch

TV traffic channels are more likely to be compliant with VSL messages. Again, commuters have different preferences to get traffic updates and so disseminating traffic information through a variety of media to reach the diverse population of commuters with different preferences should be encouraged. Emmerink, et al. [44] analyzed the impact of both radio traffic information and variable message sign information on route choice behavior. The analysis revealed that the impacts of radio traffic information and variable message sign information on route choice behavior are very similar, and that route choice adaptations based on radio traffic information are positively related to route choice adaptations based on variable message sign information. Consider a driver who is traversing a road link with VSL system installed on it. This same driver receives traffic information from other sources such as the dynamic navigation system in his/her vehicle, radio, and so on. A problem could arise when a driver feeds on information from different media and these sources give contrasting information on the same incident. A traveler seeking for traffic advice, who finds him/her self in this situation, will be left in a state of confusion without knowing what to do. This bring us to the next research question:

*are there differences in traffic information provided from different sources?*

These are the questions this dissertation aims to address. Although there have been studies on the first research question, to the best of the knowledge of the author, there is currently no study comparing the quality of traffic information from different sources.

## 1.3 Research Objectives

The main objective of this research work is to establish whether there exist inconsistencies in advanced traveler information provided from different sources. For this purpose, a quality analysis method for determining the inconsistency needs to be developed.

The main research objective, will be achieved by working on the following specific goals:

- Review of literature on existing methods of measuring the quality of real-time traffic information.

- Developing new methods to assess the different features of variable speed limit systems.

- Comparative analysis of VSL and RTTI through qualitative study.

- Quantitative comparison of VSL and RTTI.

- Testing of the developed methods through case studies.

The evaluation of these different sources of information is needed to guide ATIS users chose the provider with the best quality or assist the provider to improve on their service quality.

## 1.4 Scope of Study

The VSL and data for real-time traffic information for navigation systems, provided by a private provider in Germany, were used as subjects for the study.

A six lane freeway, autobahn A99, near Munich, Germany, was chosen as the test site. This road section has a VSL facility outfitted on it. Real-time traffic information is also broadcast on the section.

## 1.5 Research Design

The research methods will be elaborated in Chapters 5 & 6, but in this section the designed framework to be used in answering the aforementioned research questions is briefly explained. Understanding how ATIS works is very crucial in order to ensure a good review of the different components of the system. Therefore, the process chain, specifically of VSL and RTTI for navigation systems which are the focus of this research, must be well understood. Knowledge on existing methods, used to measure ATIS quality, is also important in order to identify research gaps which need to be closed. Because of this, extensive review of past as well as state-of-the-art literature should be carried out.

For VSL systems, the method developed for their assessment should be able to evaluate the different features (i.e., incident detection, warning efficiency, and ability to smooth traffic) independently. The reason being that different VSL installations are implemented, all over the world, with different control strategies.

A "stand-alone" method to evaluate each feature should be the target. For the comparison of the two information sources, a qualitative analysis will describe and provide more insight on their characteristics. A quantitative measure, taking into consideration the space-time representations of the traffic information from the different sources, will grade their quality. The research design is as shown in Figure 1.2.

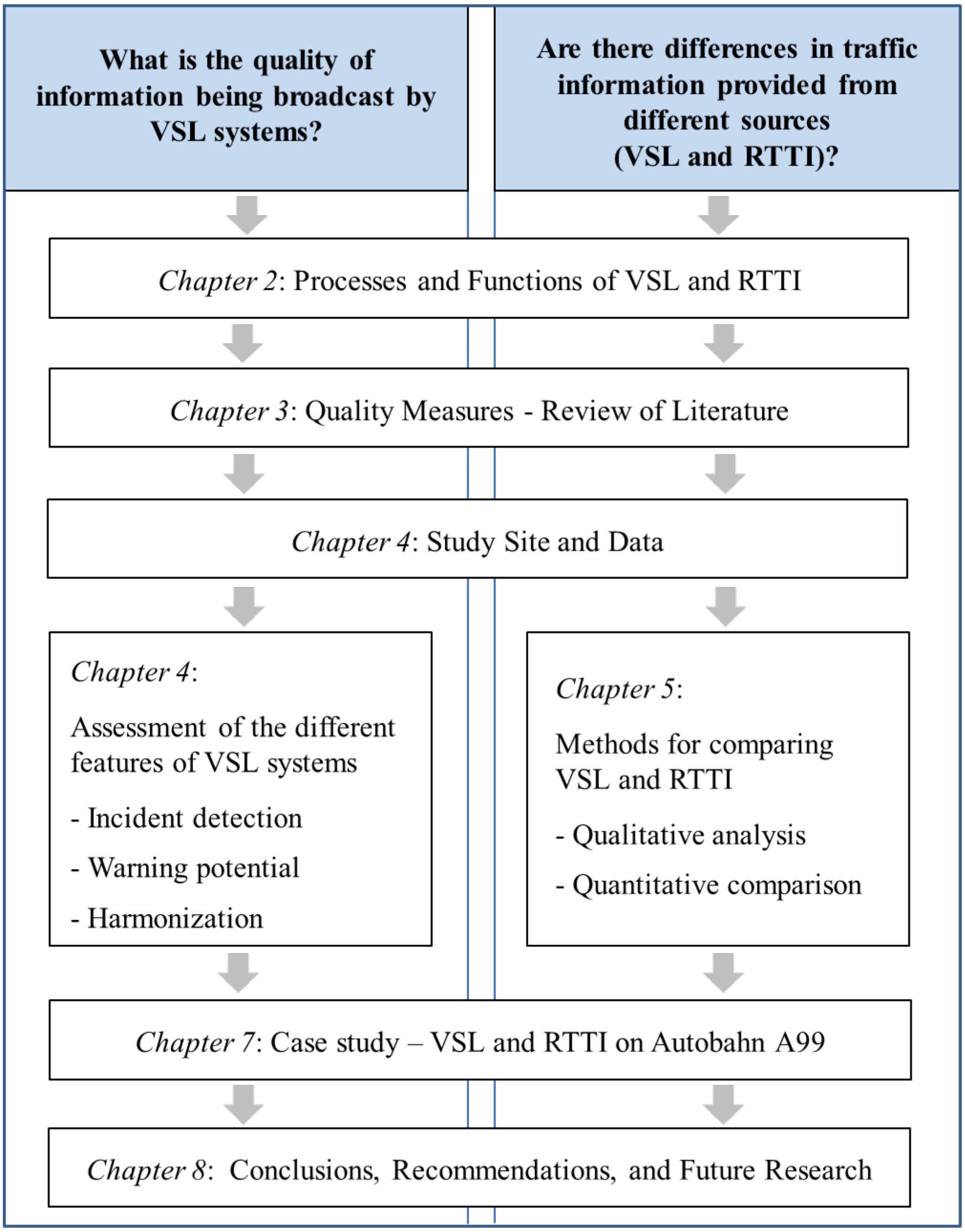



Figure 1.2: Framework for research work

## 1.6 Structure of Dissertation

In this first chapter, the subject of dynamic/active freeway traffic management has been introduced. The justification, objectives, and scope of the study have also been given. The rest of the dissertation is segmented as follows: The process chain of both the VSL and RTTI, from the data acquisition stage till the time the information is transmitted to a third party, are described in chapter two. This involves data collection methods, control strategies, and technologies for transmitting the information. Benefits from implementing the systems are also stated. Chapter three looks at earlier researches on the motivation, perception, and perceived quality of traveler information systems. The chapter continues with a review of quality and simulation methods which have been used to assess traffic information. It concludes with a summary of the reviewed literature and identification of research gaps which need to be addressed. Next, the study site and data are described in chapter four. Procedures for preparing the data for analysis are also explained in this chapter. Methods developed for analyzing the different features of VSL and comparison of VSL and RTTI systems are presented in chapters five and six, respectively. Detailed information of what informed the choice of the methods and their theoretical explanation are given. In chapter seven, the methods developed are tested in case studies. The different features of the VSL system at the study site are analyzed and its performance compared to RTTI. The final chapter gives a summary of the research project, make recommendations, and provide outlook for future research.

# Chapter 2

# Processes and Functions of VSL and RTTI

VSL and RTTI systems present traffic information to motorists and travelers. The information displayed by the service providers is supposed to reflect the traffic situation on the ground. A high quality data collection, processing, and transmission is required. This chapter describes the procedures used by the providers of traffic information from the data acquisition stage to the time the information is transferred to the consumer. As assessment is tied to the goals and standards of the system being assessed, understanding the processes of the systems is key for developing any evaluation measure.

## 2.1 VSL System Information Process Chain

Earlier VSL systems were manually controlled. The data, which informed the control, were usually based on images from video cameras [45–49]. Supervisors and control room staff monitor the traffic situation via the cameras and decide on the appropriate speed or warning sign to display. For the system to be able to react to changes in traffic conditions, the operators need to be present at work. Therefore, monitoring long stretches of roadway continuously require more personnel. Even with this, there is the tendency of the operators, being overwhelmed by large numbers of control measures to be taken or by time pressure. Presently, automated systems are generally preferred because of their ability to deal with the dynamic nature of congestion more effectively by removing the human operators and their associated limitations. This study focuses on automatic controlled VSL systems and their processes are discussed in the subsequent sections.

### 2.1.1 Data Collection and Description of VSL Systems

Traditional on-road sensors such as dual inductive loop detectors, embedded in the road, collect information on vehicle speeds, flow, density, occupancy, and so on. With the recent technological developments, new sensors for traffic data collection such as ultrasonic and acoustic sensor systems, magnetometer vehicle detectors, infrared systems, and LIDAR light detection and ranging are also in use [50–55]. Some of these new methods of traffic data collection do not need to be installed in the road. But, they could be mounted on overhead gantries or placed as roadside devices. The collected information is instantaneously transmitted to a traffic control center and analyze. At the center, the control system automatically selects the applicable speed and/or message based on the collected data. Several speed control algorithms are in operation and can be found in the literature (e.g., [48, 56–66]). Their categorization is discussed in the next section. In Germany, the MARZ algorithms [67, 68] implement both automated VSL and driver information system. The algorithms detect and issue the appropriate speed limit and/or messages based on segment circumstances. When an incident is detected, the system reacts accordingly and reduces the speeds of upstream traffic incrementally so that oncoming traffic travels through the problem area at a safer, slower, and more consistent speed. Consistently varying speed limits in multiple longitudinal locations have a greater impact on speeds than a single sign.

The variable speed limit signs, which communicate the information to motorists, may be placed on the shoulders of the road. Typically, they are assembled on an overhead gantry structure and placed across all lanes to increase their visibility to drivers. Mostly, the same speeds are always displayed for each lane at each gantry. Also displayed between each speed limit sign is advance driver information (which can be in the form of a symbol) to let the driver know of any warnings, prohibitions, or both ahead of the road. It has been established that compliance levels are higher if the speed limits are accompanied by explanation of the reason behind the display [69]. First generation VSL installations displayed their messages and symbols in monochrome or mono-color. Presently, display is in full-color. Sometimes, speed cameras are also installed to ensure compliance of the displayed speed limits. Some VSL systems incorporate a so-called remote weather information system (RWIS) to monitor the weather (e.g., rain, snow, and fog) and pavement conditions (e.g., slippery road) that may adversely affect traffic operations. Under such circumstances, speed limit selection may not be based only on the traffic condition, but also on weather. Human operators are able to take over the control (i.e., absolute priority) of automated systems when it becomes necessary. Real-time traffic information (e.g., from Police and construction companies) on incidents such as crashes, constructional works, and demonstrations which cannot be detected are, in many cases, integrated manually into the system. However, these information entered manually should be removed immediately from the system as soon as their application becomes no more relevant. Figure 2.1 and Figure 2.2 show an example of VSL system in Germany and the various speed limits and messages displayed to drivers, respectively. Explanation of all the message symbols in Figure 2.2 can be found in [70].


Figure 2.1: Example of VSL system in Germany.

### 2.1.2 Control Strategies

Garcia-Castro & Monzon [71] classified current VSL control systems into two categories:

- scheduled variable speed limit and
- dynamic speed limit systems.

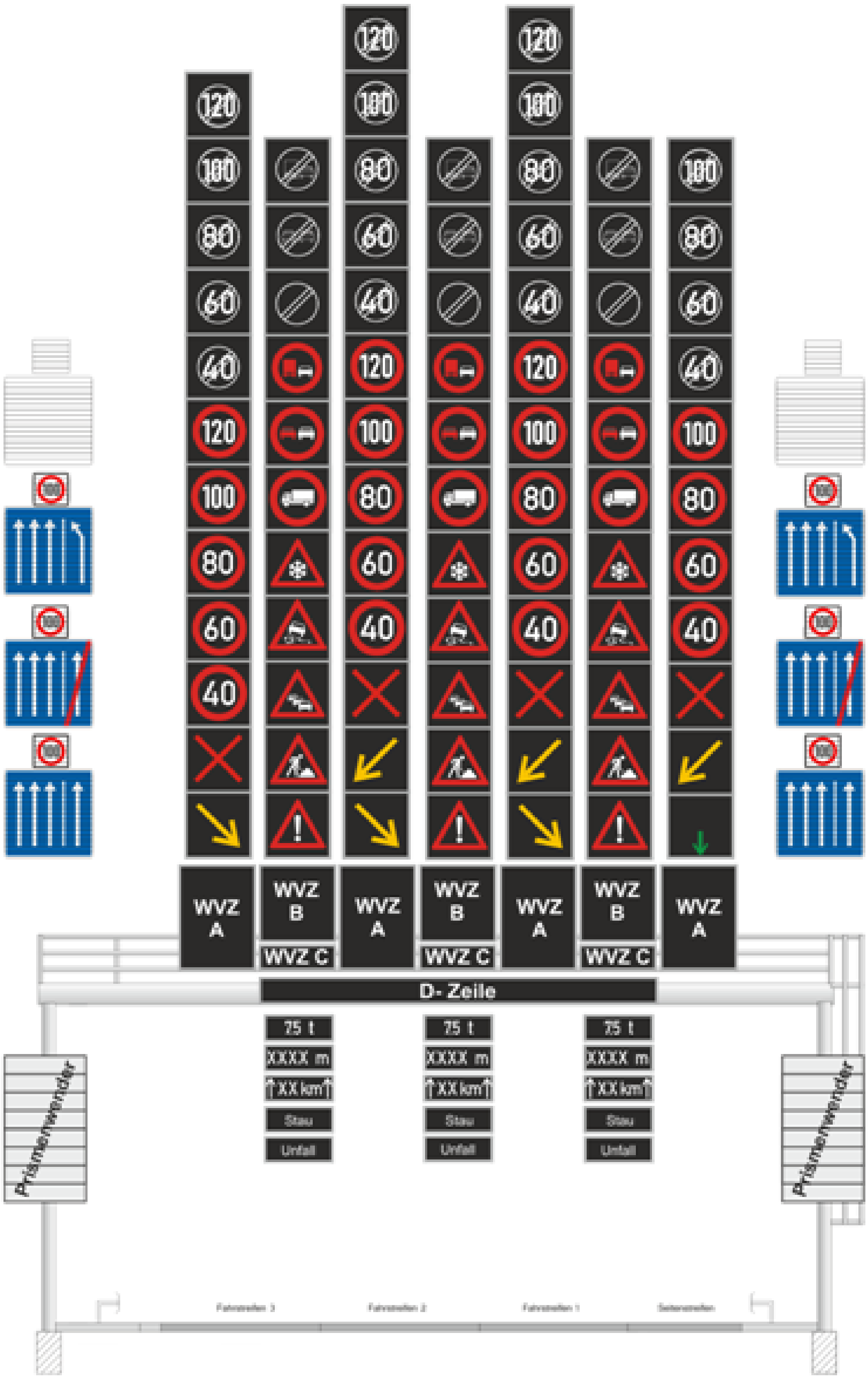



Figure 2.2: Messages and speed limits displayed by the VSL system in Germany (Source: [70]).

Scheduled VSL systems depend on a pre-established timetable based on historical data on the section of roadway. Traffic data, gathered over the periods and analyzed, can reveal traffic characteristics. With the knowledge in the traffic pattern, managers design speed limits to be displayed for particular times throughout the day. Designated speed limits are automatically displayed at their respective times. This control procedure works well with everyday "rush-hour" traffic (i.e., recurrent congestion). The problem with the scheduled VSL systems is that it is unable to deal with non-recurrent congestion, induced by incidents like traffic crashes, which can arise at any time and at any location of the road. Effects of inclement weather on traffic is also difficult to integrate into the system. Unfortunately, over 50% of traffic delays are attributed to non-recurrent congestion sources [72, 73]. Therefore, application of scheduled VSL will mean that a significant proportion of congestion will not be dealt with.

Dynamic VSL systems, on the other hand, use real-time traffic data and weather information. Control strategy could be grouped into two [48]:

1. Heuristic or decision based approaches and
2. Optimal control approaches.

### Heuristic Approach

Heuristic control algorithms use predefined rules, mostly based on practical experience, for control decision making. To any incident detected (i.e., an output from the automatic incident detection algorithm), a corresponding control action is assigned. From the input data (i.e., data collected from the inductive loop detectors, e.g., speed, flow, and occupancy or the weather information system which inform the choice of a control), a corresponding control is activated. That is, there is a pre-defined control for every combination of the input data. When the updating cycle of the VSL system is reached, the new data gathered is compared with the look-up table and the applicable control selected and displayed to motorists. Some systems may also use "if-then" algorithm for the control decision assignment [48]. Road sensors are installed only at specific locations since it is virtually impossible to have them along entire road corridors. Because of this reason, input data are only available at the sensor locations. Relying solely on the input data from these locations will mean that congestion formed in-between the sensor positions cannot be detected, or the queues have to propagate to the next upstream detector location before they can be noticed. This can lead to unsafe situations. Thereby, an important benefit of VSL systems (i.e., improving traffic safety) will not be realized. To eliminate this drawback, several methods (e.g., [57, 74, 75]) have been developed which are used to estimate the traffic state in-between detector locations. Numerical or anisotropic interpolation, tracking of traffic objects, and cumulative arrival of vehicles are some of the techniques which have been used in this regard. Some of these methods, will be elaborated on in chapter 3. Heuristic control approaches employ techniques to also coordinate the speeds displayed on successive gantries.

As mentioned, a VSL system, in addition to traffic flow control, may also use remote weather information system in deciding the control action. In this instance, the minimum of the two control decisions (i.e. from traffic flow and weather information) takes precedence. Heuristic control decisions can be changed based on experience gained over time from running the system. The main advantage of this control approach is that it is simple to use.

#### Optimal Control Approach

The switching of the displayed speed limit in optimal control approaches may also be dependent on input data such as traffic speed, flow, occupancy, density, or weather. According to Vukanovic [48], when making the final decision on the control based on the traffic situation, optimal control approaches use the traffic flow model to estimate the influences of different speed limits.

Link control measures such as the VSL usually operate based on local data (e.g., loop detector data). However, network-wide control based on global data is useful and has many advantages over local control [76]. The reason being that resolving a local congestion problem may mean, running faster into the next downstream congestion, exacerbating the situation at that location. Overall, there is not much benefit in terms of the total time spent (TTS) in the system as the gained time from the localized solution is erased downstream. Coordination of control systems is very important in order to prevent the migration of the problem to other locations. Therefore, tackling the congestion problem on the network level is encouraged.

Apart from dealing with congestion globally and coordination of control signals, prediction of the evolution of traffic on links or road networks are also needed to achieve optimal control. Prediction is required for the following reasons [77]:

- if the formation or the arrival of a shock wave in the controlled area can be predicted, then preventive measures can be taken and
- positive effect of speed limits on traffic flow is not observed instantaneously. Therefore, prediction should be made, at least, up to the point where the improvement can be observed.

Hegyi [78] described two forms of optimal control approaches: open-loop and closed-loop structures. With the open-loop structure, the inputs data have to be completely and exactly known before the prediction. For the closed-loop, the current traffic situation is regularly fed back to the controller, and the controller can take the new data into consideration and correct for prediction errors. That is, the prediction model can be changed or replaced during operation. There are several models in the literature that are used for this purpose [76, 79–81]. The model employed for the prediction is a very important aspect of optimal control. The accuracy of the predicted component is dependent on the model and the input data. Optimal control approach with a traffic flow model, in general, suffers from the same limitations as the traffic flow model itself [48].

### 2.1.3 Benefits of VSL Systems

VSL evaluation studies have been carried out to investigate the impact of the system on traffic flow characteristics, safety, environmental pollution and noise. Whereas the VSL system has been found to improve safety, vehicle emission, and noise pollution, there is still no consensus on the ability of the system to improve traffic flow.

#### Traffic Flow

Prevailing traffic speed is a key metric that directly reflects certain aspects of the road such as traffic performance, road safety, vehicle emissions, and noise pollution [71]. A traffic management system which implements variable speed limit control strategy aims to reduce speeds to stabilize and smooth traffic flow based on the prevailing traffic volume or density (i.e., harmonization). Harmonization principle, employed in VSL controls, is motivated by the fundamental diagram of the speed-flow curve. As shown in Figure 2.3, the optimal speed, $u_0$, is the speed at which maximum flow is achieved. That is, the highest throughput at the nearing point of traffic breakdown ($q_{max}$) on a given section of roadway is achieved at a speed which is lower than the free flow speed ($u_f$). It is, therefore, possible to increase the operational efficiency of a road by slowing down vehicles in advance before reaching a higher density area. While VSL systems have not been established to increase traffic flow [82, 83], researchers have argued that its safety improvement ability will result in decreasing congestion due to traffic crashes. It has been established that significant proportion of road traffic delays are caused by incidents [84–87].

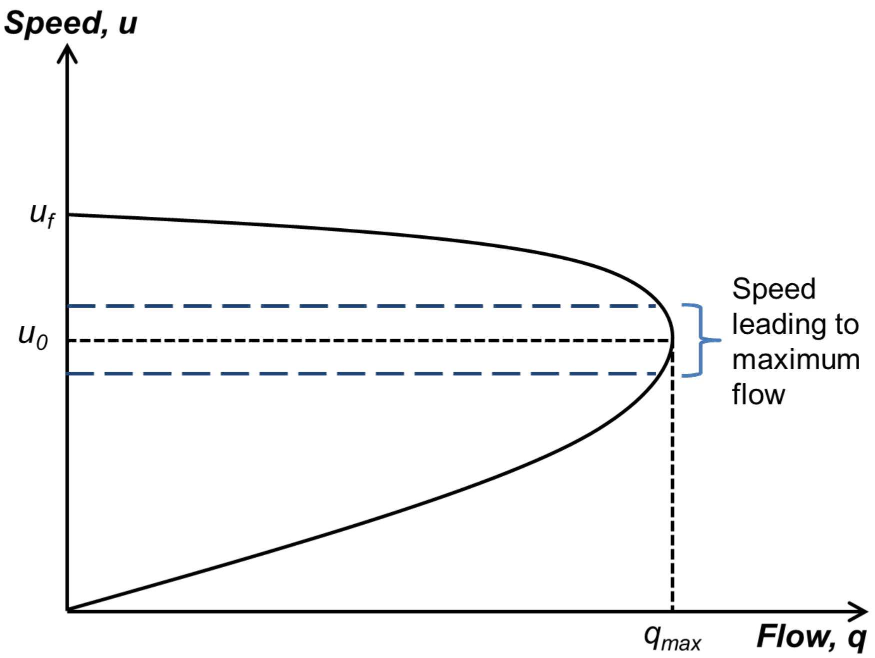



Figure 2.3: Fundamental diagram of speed-flow curve, where $u_f$ = free flow speed, $u_0$ = optimal speed, $q_{max}$ = capacity.

#### Road Traffic Safety

High speed variance is likely to increase the number of crashes [88–94]. Therefore, harmonization of traffic, which results in low speed differential, has the potential to reduce the number of crashes. Indeed, this fact has been confirmed as VSL evaluation studies have reported decreases in the rates of crashes after implementation [45, 47, 59, 68, 95–98] . Uniform headway distribution and lower speed differences between driving lanes and between consecutive vehicles reduce lane changing maneuvers, which lead to traffic conflicts, thereby preventing crashes.

**Noise and Environmental Pollution**

It has been established that traffic congestion increases emissions of greenhouse gases and pollutants like particulate matter. Congestion mitigation strategies that reduce severe congestion and increase traffic speed, and speed management strategies that bring down excessive speeds to more moderate levels such as the VSL system reduce carbon dioxide emissions [99, 100]. Bel & Rosell [101] also noted that smoothing traffic flow decreases noise pollution and reduces environmental pollution as stop-and-go waves from unsynchronized traffic increase vehicle emissions .

## 2.2 RTTI Process Chain

RTTI providers can use data from the primary stationary inductive loop detectors, which in most cases are owned by the government, for broadcasting messages. The high cost of installation and maintenance, make it practically impossible to install detectors on the entire road network. However, new methods for recording traffic situations such as the floating car data (FCD) and floating phone data (FPD) now enable private service providers to offer their services without necessarily having to rely solely on stationary detector data.

### 2.2.1 Floating Car Data

GPS devices, installed in vehicles, are able to obtain the geographical locations and instantaneous velocities with a high decree of accuracy [102–104]. Automatic vehicle location (AVL) technology has also been employed in this direction [105]. AVL determines the positions of vehicles and transmits it to a vehicle tracking system at regular intervals. Another source of FCD is personal navigation devices (e.g., in-built or mounted vehicle navigation devices) with embedded augmented global navigation satellite system (GNSS) receivers [106]. The navigation device receives traffic information from the control and at the same time transmits information from its current position to the control. FCD technology gathers only basic data such as position of the vehicle and the direction of travel. A later FCD technology, called extended floating car data (xFCD), includes more detailed data gathered by sensors of the vehicle, for example, rain sensors [107, 108].

Alternatively to devices in the vehicle, FCD can be collected by short-range communication when the vehicle passes the location of a roadside unit [109].

The main disadvantage of FCD method is its penetration rate as getting representative number of vehicles fitted with the GPS or AVL gadget is difficult to achieve on a network level. Notwithstanding, some providers have used taxis, buses, fleet, and service vehicles (e.g., DHL and FedEx) which are constantly on the road for FCD collection to increase coverage. With the increasing number of vehicles with in-built and the availability of mounted navigation devices on the market, the penetration rate of FCD will further increase.

### 2.2.2 Floating Phone Data

The position of mobile phone, of person(s) in vehicles, is regularly transmitted to the network provider usually by means of triangulation or other techniques such as handover [55]. With handover, movement of a cellular phone is detected and recorded when the phone is moving away from the area covered by one cell (i.e., the base station from where the call is being made or currently is) and entering the area covered by another cell. The positions and times of the handover are then used to estimate the travel times between phone cells. The mobile phone does not need to be in use, but must be turned on. FPD works precisely, particularly, in urban areas where there are lower distances between cellular phone antennas.

FPD is perceived to be a cheaper alternative to the conventional "in situ" detectors, and even the FCD as no additional gadgets are required to be fixed. However, there are concerns about the extent to which irrelevant data can be filtered. Pedestrians walking along a road can be mistakenly sampled as vehicles, and buses with more than one person using a phone can be sampled as multiple vehicles [107].

### 2.2.3 Data Fusion

Data fusion brings together data from several sources, available to a provider, on a single platform. The advantages of fusing data are that gaps within the data are closed and thus become complete. Data ambiguity is also reduced while extending spatial and temporal coverage [110]. Eventually, accuracy is improved than could be achieved by the use of a single data source. Techniques for data fusion have been drawn from a wide range of areas including artificial intelligence, pattern recognition, statistical estimation and inferences, signal processing, and other areas [110, 111]. Several frameworks for fusing data for ATIS have been developed and can be found in the literature. Faouzi et al. [111], grouped these techniques into three categories:

1. Statistical approaches – e.g., multivariate statistical analysis and arithmetic mean approach,
2. Probabilistic approaches – e.g., Bayesian approach, maximum likelihood method, and Kalman filter based data fusion, and
3. Artificial intelligence - e.g., neural networks.

Imperfection and diversity of technologies used in data gathering and the nature of the application environment, however, make data fusion a challenging task [111].

### 2.2.4 Transmission of Data

The mobility service providers process the available data, integrate, and transmit them to the vehicles, smart phones, and so on of the customers through traffic message channel (TMC) technology. The processed traffic information is digitally coded into radio data system (RDS) and transmitted via conventional FM radio broadcast. It can also be transmitted on digital audio broadcasting (DAB) or satellite radio [112]. RDS-TMC can embed only a small amount of digital information. A new technology of delivering traffic information to customers, known as TPEG (transport protocol expert group), is also in use. It transmits information via digital broadcast formats such as digital audio broadcasting (DAB) or internet. An advantage of TPEG is that in addition to traffic congestion information, other information on incidents, travel time prediction, weather, parking, fuel station locations, and prices can be broadcast. The real-time information can be read by a synthetic voice aloud or displayed as a text message, an icon, or a color-coded map which allows drivers the freedom to decide for themselves the information's applicability and its effect on their choice of route.

The speeds broadcast, as transmitted by RDS-TMC or some providers who use TPEG, are done per segments. The transmission of a referenced location (i.e., sending or receiving location information) can be described as encoding the location at the sender's side, transfer of the code to the receiving system, and decoding the code at the receiver's side [113]. The location referencing, used in RDS-TMC in collecting and broadcasting information for segments, are pre-coded (i.e., TMC segments). Each TMC segment has a location code. The codes of the locations are added to their corresponding locations on both the sending and the receiving maps. From [113], the process of encoding is looking up the location code in the map belonging to the relevant location. In the same way, the process of decoding is finding back the location code in the map and looking up the corresponding location. Geographical coordinates are used in the location referencing. A draw back with using coordinates for location referencing is that the maps at the sending and receiving end have to be the same. Otherwise, the decoded location (position on the receiver map) may not be found or will be inaccurate. To eliminate this problem, TPEG uses the so-called OpenLR technology. The advantage of OpenLR includes its ability to handle map differences caused by different map vendors and versions. This means that unlike the RDS-TMC location referencing system which has pre-coded locations and therefore has limited number of locations which can be transmitted, OpenLR is limitless. With OpenLR, every location in a map (e.g., nodes) can be transferred [113]. It is therefore now possible to transmit traffic information for only problematic locations within a "TMC segment." With RDS-TMC technology, the whole link would have to be indicated as problematic.

The schematic representation of the processes for the VSL system and RTTI are as shown in Figure 2.4.

### 2.2.5 Benefits of RTTI

Generally, RTTI has been established to improve incident management and impact positively on traffic on entire road network by affecting travel behavior. When traffic information is presented to drivers and commuters, it enables them to decide their:

- departure time (e.g., change of travel plans to when the road is free from congestion),
- route (use an alternative road with less traffic),
- mode (e.g., use the train instead of vehicle if the road is jammed), and
- destination (e.g., shop at target "B" if your preferred shopping location is

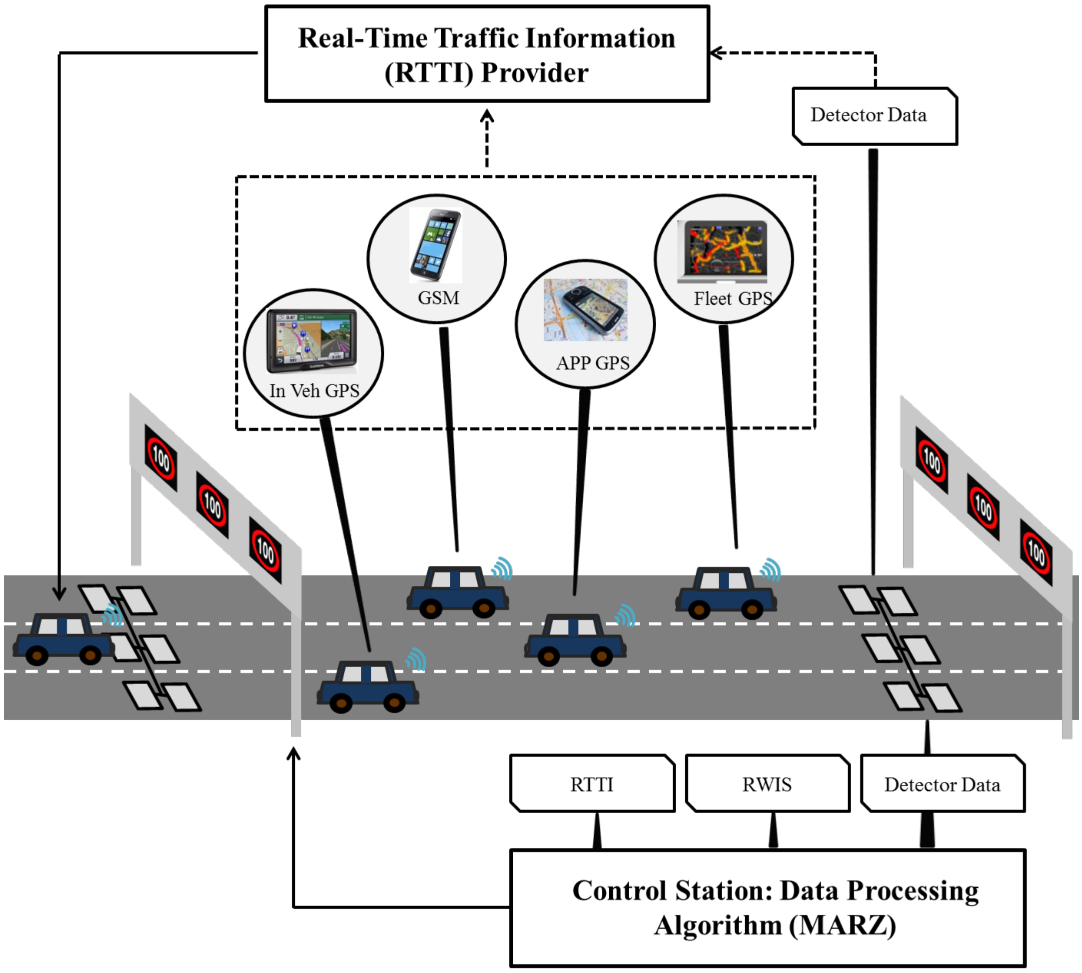



Figure 2.4: Process chain for VSL and RTTI.

"A," but there is a heavy traffic on the way to "A").

Consequently, RTTI results in an optimal use of the existing road infrastructure.

## 2.3 Functional Differences between VSL and RTTI

VSL and RTTI are expected to present traffic information to drivers and commuters. However, there are some functional differences between the two systems. Whereas RTTI intends to show the actual speed within the TMC segment, speeds displayed by a VSL gantry may not necessarily represent the prevailing speed for the segment. Instead, it may be to harmonize traffic flow or prepare drivers for a downstream situation. But, the speed display for a VSL segment must not differ significantly from the next segment downstream, which may represent the actual traffic situation. As drivers also tend to travel at speeds closer to the displayed speed limit, generally, the posted speed turn to influence the prevailing speed.

Depending on the control strategy, VSL may be obligatory. In this instance, drivers are mandated to comply with the speeds displayed or they face penalty from law enforcers. RTTI, on the other hand, is advisory.

# Chapter 3

# Quality Measures - Review of Literature

Although this dissertation focuses on quality evaluation of advanced traveler information, there have been studies, both through direct and surrogate measures, describing various methods of assessing ATIS on link sections and on entire road networks. Some of these earlier studies, as well, hold important lessons on the motivation of the need, perception of motorists, planning, and implementation of ATIS. Generally, these research works can be categorized into three (3) groups:

1. Qualitative,
2. Quantitative, and
3. Simulation.

This chapter discusses characteristics that are important for the application of ATIS, its effectiveness, and approaches which have been used to measure the quality of ATIS.

## 3.1 Qualitative Methods

Qualitative methods have been used to assess the quality and effectiveness of ATIS. These studies, mostly, employ questionnaire surveys to establish the perception and understanding of road users on attributes such as awareness, usefulness of the information, satisfaction, accuracy, use in efficient travel planning, and responses to the traffic information (e.g., change of route). Researchers such as Emmerink, et al. [44] believed that since traffic flows are simply the aggregation of individual decisions, road users' behaviour will completely determine whether these new technologies are able to meet their objective of using scarce road space in a more efficient manner. Emmerink, et al. [44] were of the view that even the most sophisticated ATIS application might be unsuccessful if we are unable to understand the behavioral consequences in advance. Thus, obtaining a greater understanding of the impact of ATIS on drivers' behavior is extremely important for judging the performance and market success of telematics. Again, as reported by [114], understanding traveler response to new technologies is at the core of understanding which innovative traveler information systems will be successful. A high-quality traffic information system, from the road users' perspective, should have the following attributes [115]:

- The travel time, incident, and other traffic information provided by the system has to be **accurate**, **reliable**, and **useful** to drivers. More importantly, it must result in travel time savings for road users.

- The system must be **easily accessible** (through different media) and has a wide coverage. Moreover, the information provided must be easily understood by drivers, that is, drivers must be easily aware of the information provided by the system to make informed decisions.

- The information provided by the system should allow users make **correct decisions** in terms of departure **time**, **mode**, and **route choices**. This, in effect, refers to the utilization of the traffic information provided by the system.

- The system has to be deemed necessary by drivers for travel and has to meet users' expectations.

Some relevant qualitative studies which have been directly or remotely used to measure the quality of ATIS are described in the following.

Peng, et al. [116] studied the effectiveness of VSL systems in inducing motorists to divert during congestion on incidents. The study was conducted in Milwaukee, Wisconsin, USA. A revealed-preference survey at the immediate vicinity of the VSL revealed that nearly two-thirds (62%) of the respondents obtained traffic information from the system more than once per week. Three-quarters of the motorists surveyed believed that arterial VSL systems were useful or somewhat useful in providing travel information, and 66% of those surveyed changed their route at least once per month because of the information received from the arterial VSL. Based on these results, the authors inferred that motorists are responsive to messages displayed by arterial VSLs, arterial VSLs have an important impact on motorists' travel behavior and are thus a key component in a comprehensive traffic management system. The study noted that propensity to divert was correlated to the frequency that a driver encounters an arterial VSL, motorists' perception of the VLS information as useful, and motorists' trust in the accuracy of the VLS information.

Richards & McDonald [117] also used revealed preference questionnaire survey and travel diaries to evaluate the variable message signs in an urban road network in Southampton, UK. The researchers asserted that user acceptance or customer satisfaction of a traffic information service is typically assessed using three main indicators: awareness, use, and satisfaction/worthiness of the system. The research focused on user acceptance of VSL, in terms of their perceived effectiveness and usefulness, and aimed to enhance the understanding of driver response to VSL messages. For any type of traffic information system, an understanding of user response is important since effectiveness is wholly dependent on user reaction to the displayed information. Some commuters sampled stated that they had diverted to an alternative route during the travel diary week as a result of VSL information. The study established that the VSL messages were well-understood and legible, and also indicated that a default VSL message reporting no problems in the network can indirectly affect a driver's route choice.

Peeta, et al. [118] investigated the effect of different message contents on driver response under VSL. The study hoped to establish if the message content is a significant factor in driver route diversion propensity. The method employed was on-site stated preference user survey. Logit models were developed for drivers' diversion decisions. The analysis suggested that content in terms of the level of detail of relevant information significantly affects drivers' willingness to divert. Other significant factors that affected driver diversion tendency included socio-economic characteristics, network spatial knowledge, and confidence in the displayed information.

Raub [119] studied how commuters view travel information and how they might respond to better information. The study aimed at, inter alia, validity of traffic information, content, and how consumers want to receive it. The method employed was questionnaire survey and the questionnaires were distributed and completed via the internet. The study found out that majority of the travelers use trip information prior to their morning commute, but far fewer use it prior to the evening commute. Generally, users found traffic information to be somewhat accurate and useful. Again, it was established that if the respondents could be provided with reliable information, they would access it and consider changing departure time and route. Consumers indicated preference for different media to receive traffic information at different times of the day. In the morning, they wanted the information from the broadcast media. At work, they wanted it by e-mail or the Web.

In order to assess the impact of travel information sources, Yim, et al. [114] developed a comprehensive conceptual model on the basis of information processing and traveler response. The effects of different information sources, content, and quality on information access and travel behavior were studied using empirical evidence from several behavioral surveys conducted in the San Francisco Bay Area, California, USA. The authors argued that understanding traveler response to new technologies is at the core of understanding which innovative traveler information systems will be successful. It was found that approximately two-thirds of respondents use dynamic information either regularly or occasionally. The respondents, according to the study, use a variety of information sources to obtain travel information before a trip as well as when en-route, with cellular phones and the internet representing important future growth markets. Yim, et al. [114] established that the most required types of information, in order of desirability, are:

- Current traffic conditions, frequently updated;
- Detailed information about alternate routes with compared travel times;
- In-car navigational computer with a display showing roads and location of congestion;
- Estimate of delay due to unexpected traffic congestion;
- Estimate of time to get from origin to destination on various routes;
- Interactively accessible information about traffic conditions at specific locations;
- Detailed information about alternative modes, including schedules and stops;

and

- Automatic notification of unexpected traffic congestion.

Respondents, according to the study, demanded good-quality information and some were willing to pay for premium information services. The empirical evidence suggested that information helps travelers switch routes and departure times. The potential for information benefits was found to be perhaps, higher in unexpected/incident situations.

Muizelaa & Arem [39] addressed the preferences of drivers for ATIS in non-recurrent traffic situations, such as incidents, road work, and large events. The paper aimed at content and characteristics of traffic information. An internet based survey was used and the target group was Dutch passenger vehicle drivers. The data gathered were analyzed with statistical tests and a multinomial logit model. From the study, the top three preferences for traffic information content were:

- advice for the fastest route to the destination;

- location, length, cause, and expected duration of traffic jams on the complete network; and

- expected time of arrival with a margin of 5% for an advised route.

It was inferred that drivers have different needs for information in different situations. The findings also showed that users that are more experienced with traffic information have needs that are different from users with less experience. The data were further analyzed with a multinomial logit model. The most important characteristic of the information was cost. However, **reliability** and **timeliness** also contributed significantly to the utility of traffic information. The findings indicated that ATIS should be strongly adaptive to the driver and to the traffic situations at hand.

According to [120], the United States Department of Transportation (USDOT) ITS conducted qualitative market research on various traffic information concepts with drivers in congested regions. Twelve (12) focus groups were fielded in six cities (two in each location). From the survey, respondents were concerned with: accuracy, timeliness, reliability, cost, degree of decision guidance and personalization, convenience, and safety of operation.

Lappin [120] mentioned that while the opinions of these drivers were based on their experience of radio broadcast traffic information, their traffic information concerns have proven to be true of all drivers surveyed since. The first three attributes namely accuracy, timeliness, and reliability appear to coincide at first sight, but these characteristics do differ. Muizelaa & Arem [39] differentiated between them as follows. Accuracy concerns the precision of the information that is provided. Timeliness concerns the delay between the measurement of traffic and the delivering of information to the end user. Reliability then defines whether the provided information is correct.

Grotenhuis et al. [121] thought that travel information should affect customers' modal choice. Therefore, they conducted a study with the objective of identifying customers' desired quality of integrated multimodal travel information (IMTI) provision in public transportation systems. The study sample involved Dutch travelers with a substantial share of young persons. From the results, customers' desired IMTI quality can vary throughout the pre-trip, wayside and on-board stages of a journey. The study found the pre-trip stage to be the favorite stage to collect IMTI when planning multimodal travel. Wayside IMTI is most desired when it helps the traveler to catch the right vehicle en route. On-board travelers are most concerned about timely arrival at interchanges in order to catch connecting modes. Therefore, they need real-time IMTI to achieve a timely arrival. In the whole travel process, quality information to aid travel time savings, physical effort (e.g., walking, waiting, and carrying luggage), and affective effort (defined as uncertainty, worry, and stress) savings seem most important wayside. Apart from that, pre-trip search time savings are also desired, while en route affective effort is more important than cognitive effort (defined as mental effort that people use to process travel information).

Chatterjee & McDonald [122] undertook a study and the objectives included examining drivers' reactions to VSL. The paper drew together the results from VSL field trials conducted in nine cities as part of European Union (EU) sponsored research projects carried out between 1994 and 1999. Questionnaires were administered to drivers. It was found that virtually all drivers who could read information claimed to have also understood it. For drivers who noticed VSL information, an average of 32% in London, Southampton, and Toulouse said it was useful and they felt much better informed, 45% said it was useful but of limited value only, 10% said it was not particularly useful. The survey in Paris found that drivers had better regard for VSL after travel times were introduced.

The results show that for drivers who noticed VSL information, an average of 13% diverted from their intended route. The study concluded that drivers' perception of the benefits from VSL is high.

Khoo & Ong [115] established that most of the studies for measuring the perceived quality of ATIS have used attributes, and have either explicitly or implicitly assumed the attributes to be independent, and therefore cannot truly provide an overall picture on the road users' perception of the quality of traffic information system. The researchers went a step further to use structural equation modeling (SEM) to test the hypotheses on the relationship among various attributes. All important attributes which might influence the driver perceived quality of the system were investigated. Using the integrated traffic information system in Klang Valley region, Kuala Lumpur, Malaysia as a case study, it was observed that the proposed structural equation model approach allows a holistic interpretation on perceived quality of the traffic information system. The structural model indicated that the perceived quality of ITIS is influenced by awareness, utilization, perceived effectiveness, perceived necessity of the traffic information system, and driver expectations.

Table 3.1 summarizes the attributes and key findings of the above described literature.

*By measuring the respondents' attitudes towards the attributes of the traffic information, the perceived quality of the system is said to have been assessed. However, these responses are, mostly, influenced by various factors including drivers' perception and understanding of traffic information. Assessment methods based on interviews may also be susceptible to answer falsification. Kattan, et al. [43] noticed that results on the same attribute differed significantly from one city to another, depending on the network characteristics and congestion levels.*

Table 3.1: Summary literature on perceived ATIS quality

| **Study Reference** | **Objective(s)** | **Study/Survey Methodology** | **Major (Key) Findings** |
|---|---|---|---|
| Peng, et al. [116] | - Attitudes towards VSL<br>- Diversion behaviors | Revealed-preference | Propensity to divert was correlated to:<br>- Motorists' perception of information as useful<br>- Motorists' trust in the accuracy of the information. |
| Richards & McDonald [117] | - Perceived effectiveness and usefulness<br>- Establish user acceptance | - Revealed-preference<br>- Travel diaries | - Accurate VSL messages can indirectly affect a driver's route choice<br>- VSL messages were well understood and legible. |
| Peeta, at al. [118] | Investigates the effect of different message contents on driver response | On-site stated preference user survey | - Content significantly affects drivers' willingness to divert.<br>- Other significant factors include socioeconomic characteristics, network spatial knowledge, and confidence in the displayed information. |
| Raub [119] | - How consumers want to receive information<br>- Validity of traffic information content. | Internet based questionnaire survey | - Consumers indicated different media to receive traffic information at different times.<br>- Users generally find the information to be somewhat accurate and useful. |

Table continuation on next page

Table 3.1 – Summary literature on perceived ATIS quality *continued*

| **Study Reference** | **Objective(s)** | **Study/Survey Methodology** | **Major (Key) Findings** |
|---|---|---|---|
| Yim, et al. [114] | Effects of different information sources, content, and quality on information access and travel behavior. | Empirical data from behavioral surveys. | - Respondents use a variety of information sources to obtain travel information.<br>- Respondents demanded good-quality information, and some were willing to pay for premium information services.<br>- The potential for information benefits was found to be higher in unexpected situations. |
| Muizelaa & Arem [39] | - Preferences of drivers for ATIS in non-recurrent traffic situations.<br>- Content and characteristics of traffic information. | Internet based survey | - Drivers have different needs for information in different Situations.<br>- Preferences for information were advice on the fastest route, location, length, and cause of a jam and expected time of arrival.<br>- Important characteristic of traffic information were cost, reliability, and timeliness. |

Table continuation on next page

Table 3.1 – Summary literature on perceived ATIS quality *continued*

| **Study Reference** | **Objective(s)** | **Study/Survey Methodology** | **Major (Key) Findings** |
|---|---|---|---|
| Lappin [120] | What ATIS customers want. | Focus group discussion. | Drivers are concerned with:<br>Accuracy, timeliness, reliability, cost, degree of decision guidance and personalization, convenience, and safety of operation. |
| Grotenhuis, et al. [121] | Identifying customers' desired quality of IMTI provision in public transport systems. | Questionnaire survey | Quality travel information to aid savings of the following are important:<br>Travel time, physical efforts, affective effort, and cognitive efforts. |
| Chatterjee & McDonald [122] | Drivers' reactions to VSL. | Questionnaire survey. | - Respondents had better regard for VSL after travel times were introduced.<br>- Drivers perception of benefits from VSL is high. |
| Khoo & Ong [115] | Establish a relationship between different attributes use to measure perceived quality | - Revealed preference Questionnaire survey<br>- Structural equation modeling (SEM) | - Attributes used to measure quality cannot be evaluated independently.<br>- Perceived quality is influenced by awareness, utilization, perceived effectiveness, perceived necessity of information system, and driver expectations. |

## 3.2 Quantitative Methods

Past research works, have also, used quantitative methods to evaluate ATIS. These quantitative methods can be broadly grouped into two (2), namely:

- microscopic and
- macroscopic

In some countries, where the use of ATIS is popular, institutions have been set up to ensure quality of the traffic information provided. These organizations develop their own methods for the measurement. This section looks at quality assessment methods for ATIS.

### 3.2.1 Microscopic Quality Measurements

In the following, two methods for measuring the quality of traffic information by considering single vehicle-driver units (microscopic) are described. They are: quality evaluation based on floating car data (QFCD) and quality benchmark (QBENCH) methods. Essentially, a representation of the real traffic situation is reconstructed to form what is referred to as the ground truth (GT). The GT is then matched with the broadcast traffic information.

#### Quality Evaluation Based on Floating Car Data

For the QFCD model, global positioning system (GPS) trajectories, generated via probe vehicles, are used to simulate reality (i.e., GT). The method was first presented by Bogenberger & Hauschild [123]. This method was developed to aid quality assessment at areas where detector data are not available. As the probe vehicle travels through traffic message channel (TMC) segments, the segments are represented with the average speed with which the probe vehicle used to traverse it. A space-time representation of the mean speed for all TMC segments and their respective times is made. A speed threshold is defined to categorize congested areas from free flowing traffic conditions. The space-time representation is color coded, for example, red for congested regions and green for free flowing regions. The traffic information is then superimposed on it (blue color) as illustrated in Figure 3.1.

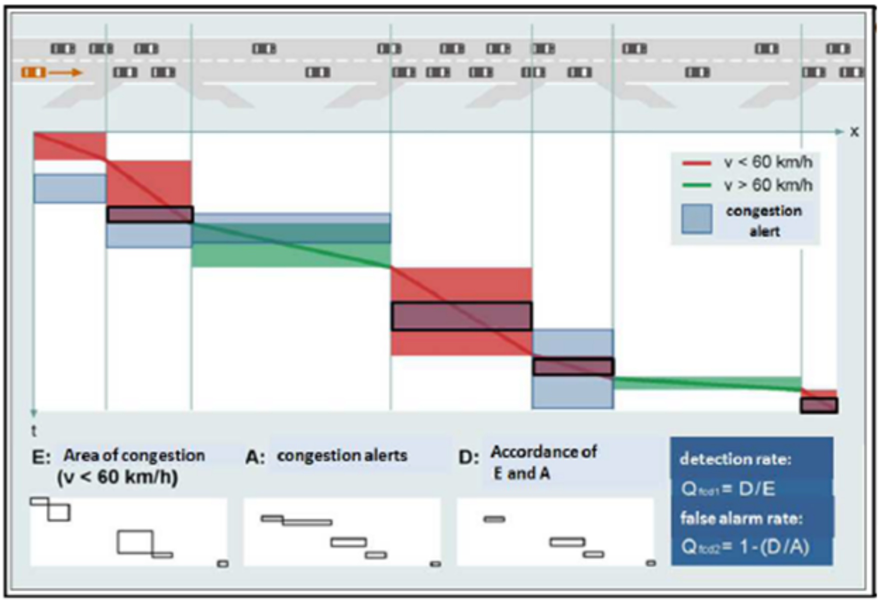



Figure 3.1: QFCD method: Superimposition of reconstructed traffic state (GT) from probe vehicles and traffic messages (Source: [123]).

Two indexes are defined to measure quality. Quality index one, $QFCD_1$, which is the detection rate (DR), describes the degree to which the traffic message coincides with the actual congestion event. Quality index two, $QFCD_2$, is the false alarm rate (FAR) and is defined as the area of the congestion message which is not covered by the real congestion event. The methods for calculating $QFCD_1$ and $QFCD_2$ are represented in Equation 3.1 and Equation 3.2, respectively.

$$QFCD_1 = \frac{D}{E} \tag{3.1}$$

$$QFCD_2 = 1 - \frac{D}{A} \tag{3.2}$$

$E$ is the area of actual congestion in the space-time diagram while $A$ is the space-time congestion area covered by the traffic information. $D$ is the intersection between $E$ and $A$.

These two indexes are then used to evaluate the quality of the traffic information. Values of the indexes range from 0 to 100%. Grades of A (very good), B (satisfactory) and C (inadequate) are implemented on the $QFCD_1$ and $QFCD_2$ quality scale diagram as shown in Figure 3.2.

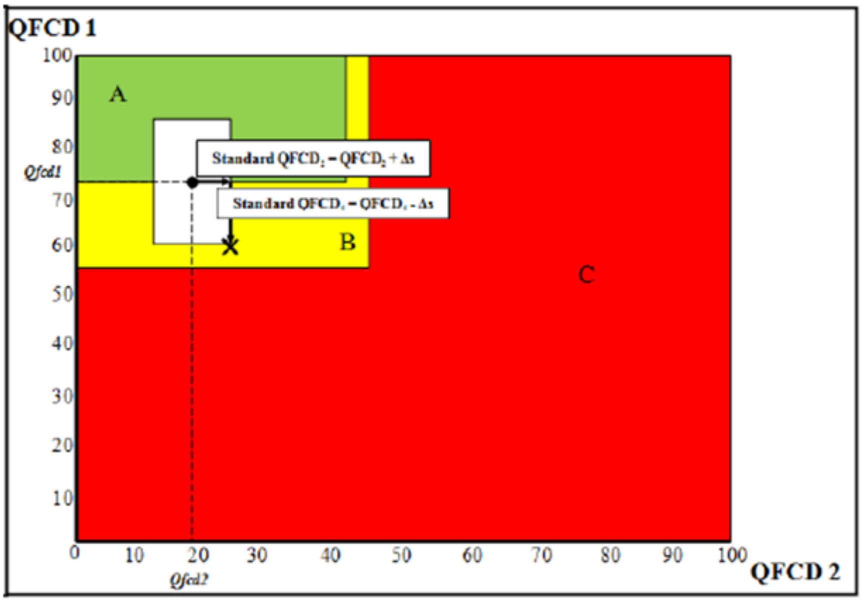



Figure 3.2: QFCD quality diagram (Source: [123]).

### Quality Benchmark (QBENCH)

From [124], detection and false alarm rates cannot be used in situations where the traffic information providers display travel time as their content. An adapted link-cost function as use in routing algorithms was employed in developing QBENCH. On a road network, links have a fixed minimum cost (in time) represented by $t_{ff}$. This cost can increase depending on the level of traffic congestion. The ground truth travel time ($t_{gt}$), which is the actual time experienced by a driver, is measured using test vehicles. At the same time, traffic information providers also broadcast the travel time, $t_{rep}$, required by a vehicle to traverse the segment. QBENCH compares the benefits of test vehicles and service providers by calculating the ratio as in Equation 3.3.

$$QBENCH = \frac{\sum_{all} B_{real}}{\sum_{all} B_{ideal}} \tag{3.3}$$

Traffic congestion occurs only at peak periods and when there are incidents. During most parts of the day, free flowing conditions prevail. Therefore, a provider just reporting free flowing condition will definitely score a high mark since misdetections will not be visible in the overall picture. To eliminate this misrepresentation, a congestion threshold ($t_{ct}$) was defined and conditions where both the ground truth and broadcast information exceed this threshold is not considered in the equation.

The ideal benefit is calculated (Equation 3.4) as the time of delay, in seconds, which was reported by the reference vehicle (i.e., ground truth) scaled by an impact factor $\varphi$.

$$B_{ideal} = \begin{cases} 0, & t_{gt} \leq t_{ct} \\ (\varphi - 1)(t_{gt} - t_{ff}), & t_{gt} > t_{ct} \end{cases} \tag{3.4}$$

The real benefit is determined based on the traffic information broadcast. This is done by calculating a loss function (Equation 3.5) that is different for overstating and understating congestion. If the expected speed is outside a defined tolerance area, it is reduced.

$$B_{loss} = \begin{cases} (\varphi - 1)(t_{gt} - t_{rep}), & t_{rep} < t_{gt} \\ 0, & t_{rep} = t_{gt} \\ t_{rep} - t_{gt}, & t_{rep} > t_{gt} \end{cases} \tag{3.5}$$

A tolerance area is defined around the ground truth speed where no loss of benefit is calculated. As speeds within congestion events are not static, there is a window function that combines larger stretches of roads to smooth travel time. That is, the tolerance and window functions take care of impacts due to infrastructure (e.g., traffic signals) and speed waves in congestion.

To avoid discontinuities outside the tolerance area, the definitions of the tolerance borders are newly defined to use traverse time $t_{lower}$ and $t_{upper}$, respectively instead of the ground truth speed $V_{gt}$. This results in $B_{lower}$ being calculated as in Equation 3.6 and $B_{upper}$ by Equation 3.7.

$$B_{lower} = B_{ideal} - (\varphi - 1)(t_{gt} - t_{lower}) \tag{3.6}$$

$$B_{upper} = B_{ideal} - (t_{upper} - t_{gt}) \tag{3.7}$$

The real benefit is calculated according to Equation 3.8. If the reported speed is free flow, the real benefit is set to zero. Since QBENCH is estimated from the difference between GT travel time and reported travel time, the same quality index might have two different connotations: understating congestion or overstating congestion. Understating congestion leads to unexpected raises in travel time while overstating leads to unnecessary detours. From [124], the effects depend on the road class. The impact factor $\varphi$ can reduce the amount of loss in benefit for specific road classes.

$$B_{real} = \begin{cases} \frac{B_{ideal}}{B_{lower}}(B_{ideal} - B_{loss}), & t_{rep} < t_{gt} \\ B_{ideal}, & t_{rep} = t_{gt} \\ (B_{ideal} - B_{loss}) + (B_{ideal} - B_{upper}), & t_{rep} > t_{gt} \end{cases} \tag{3.8}$$

As travel times do not behave linearly, it is advisable to reduce the maximum loss and gain that a single event may generate in order not to influence the overall result. For instance, for lower traverse speeds, the effect of a single event on the overall outcome may be significant. This is done by the capped value which is defined as (Equation 3.9):

$$B_{cap} = \lambda * (\varphi - 1) * (\frac{100}{\delta} - 1) * t_{ff} \tag{3.9}$$

where $\delta$ is the percentage of free flow speed for a segment below which it is considered congested, and $\lambda$ is the number of correctly reported congestion necessary to compensate for missing the worst case congestion. Furthermore, $B_{ideal}$ should be bounded below by a minimum congestion time. These values differ for freeways and non-freeways and have to be defined according to local conditions.

*A major problem with the use of probe vehicles to reconstruct reality, as in microscopic quality measurement, is their penetration rate. Practically, as it is the case now, it is capital-intensive deploying a representative number of vehicles for the microscopic GT reconstruction.*

### 3.2.2 Macroscopic Quality Measurements

The basic idea for macroscopic methods for measuring the quality of traffic information is the same as for microscopic. That is, the broadcast traffic information is compared with a ground truth traffic. However, for microscopic models, GT is estimated, mostly, from inductive loop detector/sensor data. Numerical interpolation or anisotropic interpolation methods are required to estimate the GT from the point detector data.

#### Automatische Staudynamikanalyse/Forecasting of Traffic Objects (ASDA/FOTO) Travel Time Method

The GT reconstruction for ASDA/FOTO travel time method is based on Kerner's three-phase traffic theory [74, 125, 126]. Classical traffic flow theory describes two phases of traffic: free flow and congested traffic. Kerner contends that, besides the free flow traffic phase, there are two other traffic phases in congested traffic: synchronized flow and wide moving jam. Thus, there are three traffic phases in Kerner's traffic theory:

1. Free flow (F)

2. Synchronized flow (S), and

3. Wide moving jam (J)

Free flow traffic conditions prevail when the vehicle density is small and therefore there is only a negligible interaction between the vehicles. A wide moving jam maintains the mean velocity of the downstream front of the jam as the jam propagates. Contrary to the wide moving jam traffic phase, the downstream front of the synchronized flow phase does not maintain its mean velocity. Specifically, the downstream front of synchronized flow is often fixed at a bottleneck. Figure 3.3 shows a space-time representation of the propagation of the two phases of congested traffic. The front and tail locations of the jam define the spatial size and location of the jam. The ASDA/FOTO models track synchronized flow and wide moving jam objects in time and space and thus reconstruct congested traffic patterns. The tracking is also done in-between detectors. The identification of the traffic phases in congested traffic is made in such a way that if the congested state is not related to the wide moving jam, then the phase is associated with the synchronized flow phase.

Ground truth travel time estimated from the reconstruction according to ASDA/FOTO models represents reality. The red line in Figure 3.4 shows an illustration of ground truth travel time. Traffic information providers broadcast speeds for TMC segments. This speed information is then transformed into travel times ("stairs" like curves). The quality of traffic information is assessed by comparing the travel time curves in congested time periods. The closer the providers travel time is to the ground truth travel time, the better the quality of service provided.

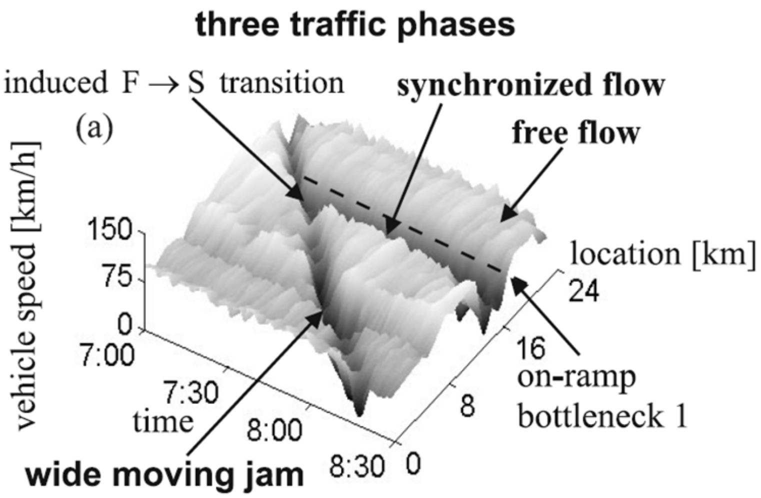



Figure 3.3: Two phases of congested traffic in Kerner's three-phase traffic theory (Source: [74]).

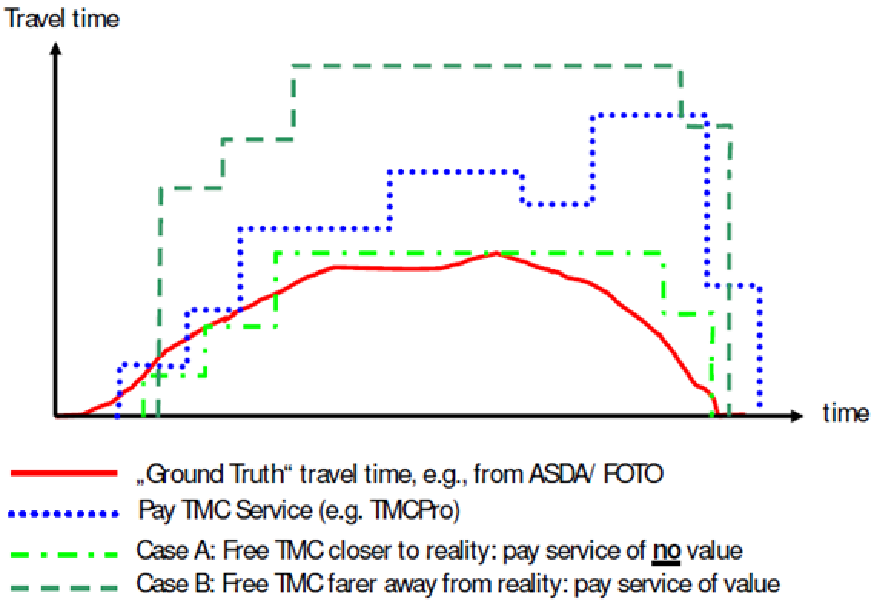



Figure 3.4: Comparing traveling services (Source: [127]).

### Qualitätskennziffer (QKZ) Method

This quality evaluation method was proposed by [128]. The QKZ method, which was developed from the concept of signal detection theory, compares the reconstructed traffic state (reality) with messages broadcast by providers of real-time traffic information. Numerical interpolation or anisotropic interpolation methods are required to estimate the GT from the point detector data [129]. The traffic messages are valid for certain road corridors and time duration. Therefore, they can be entered in a spatio-temporal representation. Referring to Figure 3.5, supposing the actual congestion areas are represented by an area $E$ and the message sign areas by $A$, the intersection area $D$ is where $E$ and $A$ match in space and time. Two indexes are defined to measure quality. Quality index one ($QKZ_1$), which is the detection rate, describes the degree to which the traffic message coincides with the actual congestion event and is calculated according to Equation 3.10.

$$QKZ_1 = \frac{D}{E} \tag{3.10}$$

Quality index two ($QKZ_2$), the spatio-temporal false alarm rate, describes the proportion of the traffic message that is not relevant to the congestion. This is also calculated as in Equation 3.11.

$$QKZ_2 = 1 - \frac{D}{A} \tag{3.11}$$

These two indexes are then used to evaluate the quality of the traffic information. Values of the indexes range from 0 to 1 or 0 to 100%. Grades from A (very good) to F (poor) in a manner similar to the highway capacity manual (HCM) [130] are implemented on the $QKZ_1 - QKZ_2$ diagram as shown in Figure 3.6. When quality index one is high and quality index two is low, the quality of reporting is graded as high.

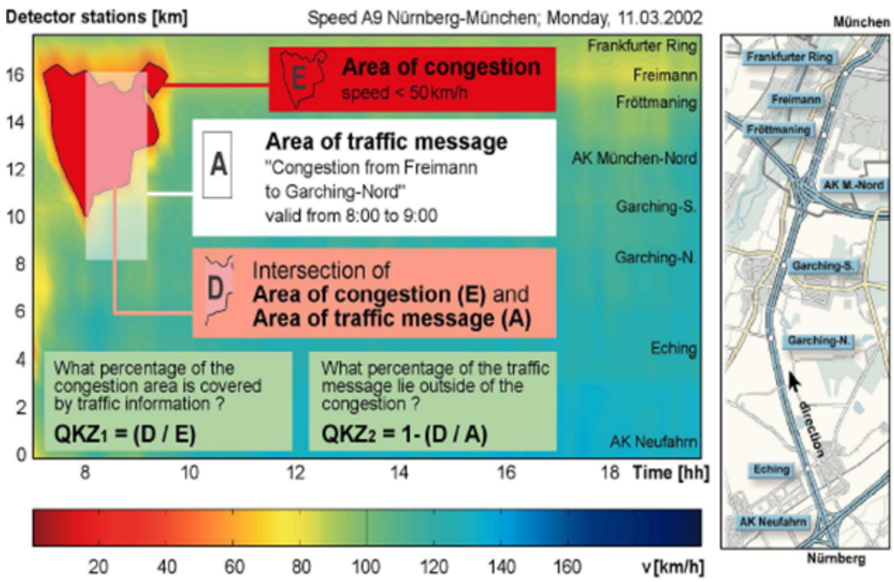



Figure 3.5: QKZ quality indexes estimation (Source: [128]).

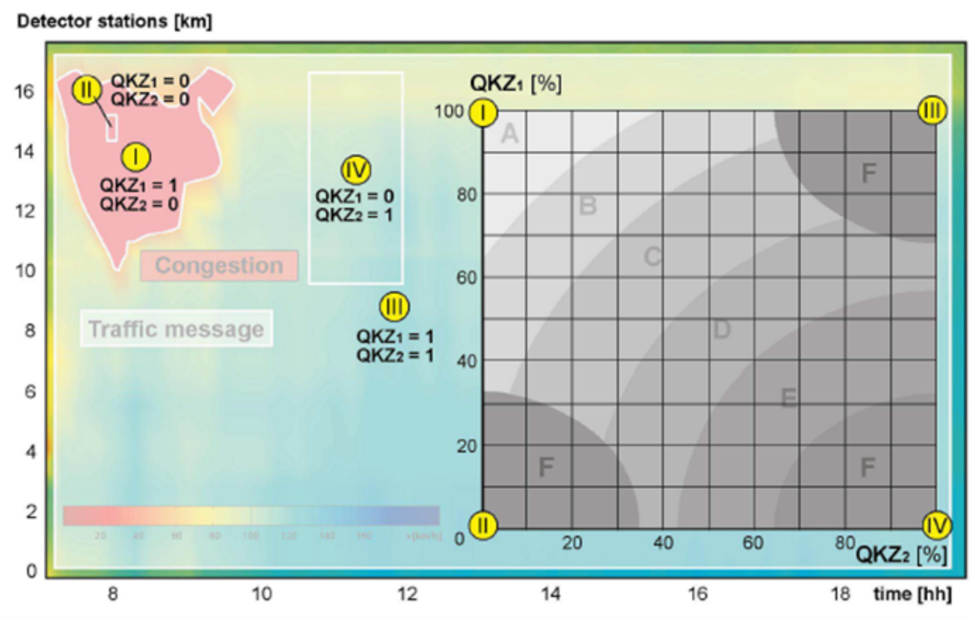



Figure 3.6: QKZ quality scale diagram (Source: [128]).

Four (4) extreme values, I, II, III, and IV, as can be seen in Figure 3.6 were identified and are explained below [128]:

### Case I

The congestion area $E$ matches perfectly with the message area $A$. Therefore, the intersection area $D$ is the same as $E$ and $A$, and $QKZ_1$ and $QKZ_2$ are 100% and 0, respectively (quality grade A).

### Case II

- The traffic information message $A$ is infinitesimally small ($A \longrightarrow 0$) but falls within the congestion event $E$. The intersection area $D$ thus approaches 0. $QKZ_1$ and $QKZ_2$ are therefore 0.

- The congestion area is very large and $E$ approaches infinity. However, the traffic report indicates much too small an area for the congestion event. $D$ is therefore 0 and the two quality indexes are likewise 0.

These situations are categorized as grade F.

**Case III**

- The traffic information message is infinitely large ($A \longrightarrow \infty$). A traffic information message is broadcast all day for an entire freeway. However, the congestion area is much smaller in terms of space and time. The intersection between $E$ and $A$ is equal to $E$. $QKZ_1$ is therefore 100%. However, since $A$ is very large, $QKZ_2$ is also 100%.
- The congestion area is infinitesimally small ($E \longrightarrow 0$). $D$ is the same as $E$ and $QKZ_1$ is thus 100%. Since virtually the entire message area ($A$) is outside the congestion area, $QKZ_2$ is likewise 100%.

These situations are categorized as grade F.

**Case IV**

The congestion area $E$ and the traffic information message $A$ do not intersect ($D = 0$). The driver obtains a "phantom" message of congestion for a traffic jam that does not actually exist. On the other hand, he does not obtain a message about real congestion into which he is actually driving. $QKZ_1$ is 0, while $QKZ_2$ is 100% (quality grade F).

### 3.2.3 Approaches Used by ATIS Quality Assurance or Certification Organizations

As mentioned, in some countries where the use of ATIS is popular, institutions have been set up to monitor and ensure the maintenance of acceptable standards for the service. The implication is that these organizations must develop their own methods for the ATIS quality testing in order to realize their mandate. These organizations are fairly young and ATIS quality methods are in their infancy. Some of the procedures, used by the ATIS assurance companies, which have been found in the literature, are discussed in the following.

**National Databank Warehouse**

For the national databank warehouse (NDW) for traffic information, Netherlands, quality of the data use in producing the traffic information is very important.

The motivation is that the quality of the data collected will have repercussion on all applications which draw from it. According to [131], initially, the focus was on availability of the data (which should be more than 97%) and timely delivery (which should be available to the user within 75 seconds). In addition to availability and timely delivery, the user should be able to rely on the quality of traffic data (accuracy and reliability). For the NDW, measuring and quality improvement is approached from the following angles [131]:

- **Data suppliers:** they are responsible for the quality of the data they gather. One of the instruments the data supplier might use is the so-called "plausible test." The plausible test measures whether the sample taken are representative for the real traffic situation. Again, the contract between NDW and the data suppliers that defines the level of quality expected from them (service level agreement (SLA)) is an important tool in discussing and improving quality of traffic information.

- **Testing by NDW:** the NDW-organization is involved in determining data quality, however, they acknowledge that quality measurement is at its infancy even at the international level. The organization started with a pilot study to develop a "quality reference system" by developing a system that will get close to establishing reality (ground truth) on traffic variables such as flow, speed, and travel time on the road. A second approach was to develop or make use of existing systems as a reference system that can be easily deployed (at low costs), but with a lower, but known quality. The idea was to finally select one of these methods as the reference system.

- **Analysis of the work processes:** This involves the audit of the processes used by the organizations in their data gathering. According to [131], the audits resulted in improvements.

Riegelhuth [132] also believed that in order for traffic information to be able to warn motorists of dangerous situations and also control and route traffic, data must be available with a high standard of quality and covering as large an area as possible. To this end, a minimum data is required on the part of the road operators in order to be able to operate traffic control systems which have a significant effect on safety with a high level of availability.

*There may be a problem when using data collected at the initial stage of the traffic information data chain to measure quality. Kusche [133] looked at the German traffic information service chain. It was noticed that there are a lot of* *industry players contributing between data collection and the display of the traffic information on an end user's device. At least, two major interfaces in the traffic information world were identified [133]:*

- *between content and service provisioning and*
- *between service and end user*

*These interfaces, sometimes, are worlds apart and an error can occur at any link of the value chain. Therefore, depending on the data collected alone to measure quality may not be the best of approaches to evaluate quality of traffic information.*

### NavCert

NavCert, which is part of the TÜV SÜD group, is an international service corporation focusing on consulting, testing, certification, and training. The organization is headquartered in Munich, Germany. NavCert is dedicated to provide validation and test in all areas in which positioning, navigation, and timing (PNT) is required [134]. From [134], NavCert has developed test and certification plans for traffic information systems and performed comparisons between traffic information systems. NavCert acknowledges that for traffic information systems, no common criteria do exist. Therefore, key performance indicators (KPIs), identified as relevant to traffic information systems to assure that the user expectation is measured were defined. The first KPI was *jam accuracy*. This determines whether traffic jams exist on any section of the considered road or not. The jam accuracy is defined as the ratio between jams reported correctly and the number of all actual traffic jams. To avoid that a traffic information system is achieving a too high scoring by just indicating for all roads the existence of traffic jam, a second KPI which is the *message delivery ratio* has been used. This is defined as the ratio between correctly reported jams and number of all reports by the specific information system. Another KPI, which is used by NavCert is concerned with *road coverage*. This is informed by the fact that drivers, after learning of congestion on a segment, would want to take alternative routes. Therefore, knowledge of the traffic information on the whole transportation network, and not just a link, is important. Road coverage is defined as the measurement of incidents for various road classes, to ascertain if all road classes are monitored [134]. According to NavCert, the most important KPI, however, is the *jam reliability*. This is defined as the ratio between reported length and delay to actual length and delay. From [134], measurements of the KPIs can be performed in two different ways, one being an observer and the other being part of the system. If a traffic information system provides information (length of congestion queue or expected delay) of an incident, the independent observer can measure the length of the incident at the time the information was provided. As part of the system, the length of an incident is measured by passing by the incident.

*Congestion has both spatial and temporal extent. Therefore, using the frequency of congestion to define quality may not be enough. NavCert did not give details on how and when the queue lengths or travel time measurements, which are used in the quality assessment, are done. The frequency at which they can carry out these measurements are also not known. Considering the dynamic nature of traffic congestion, this could be problematic. Again, there is always the problem of deploying a significant number of observers or vehicles to represent the actual traffic stream, hence such methods (i.e., independent observer or probe vehicles) lack statistical robustness.*

## 3.3 Simulation Studies

Simulation based studies have also been used to study ATIS. However, mostly, these studies have focused on the effect of ATIS on network performance. To study the effect of ATIS, researchers essentially set up a basic model of driver behavior with ATIS and secondly without ATIS. Benefit from the system in terms of travel time savings is then quantified.

### 3.3.1 Tools for the Simulations

Earlier efforts to model ATIS included the use of INTEGRATION software [135]. INTEGRATION always assigns vehicles to the shortest path and is therefore not capable to model driver behavior. DYNASMART (**DY**namic **N**etwork **A**ssignment **S**imulation **M**odel for **A**dvanced **R**oad **T**elematics) is also a simulator for ATIS network applications [136]. It incorporates [137]:

- real-time traffic flow and control simulation,
- dynamic network path processing, and

- microscopic consideration of driver response to information.

That is, DYNASMART models driver behavior and traveler information supply strategies. Each vehicle is generated and loaded onto the network on an initial path as either equipped with or without ATIS. Unequipped vehicles follow the initial path whereas equipped vehicles can switch path along the way according to different behavioral assumptions (with stochastically assigned parameters) and provided information. In earlier applications of DYNASMART, the initial path routing, which is used by all unequipped vehicles, was simply by shortest path. However, for equipped vehicles, the initial path routing is compared with the minimum of the k-shortest[6] paths. If the difference in travel time achieved by changing path exceeds a defined threshold, then a path change occurs [137]. However, the shortest path assignment of unequipped vehicles was questionable since, depending on the traffic condition, drivers may select routes with the minimum travel time which may not necessary be the shortest spatially. DYNASMART was later improved to allow for the initial assignment of both equipped and unequipped vehicles to dynamic equilibrium[7] paths provided by another model, CONTRAM [139] . Later packages for ATIS deploying planning and impact evaluation, DYNASMART-P, incorporated dynamic traffic assignment in the model [140].

**Dy**namic **n**etwork **a**ssignment for the **M**anagement of **I**nformation to **T**ravelers (DynaMIT) is also a simulation-based real-time system designed to estimate the current state of a transportation network, predict future traffic conditions, and provide consistent and unbiased information to travelers [141]. Florian [142] presented a framework for ATIS evaluation. The framework, integrates in real-time DynaMIT and a traffic management center. During real-time operation of the ATIS evaluation framework, MITSIM [143], a microscopic traffic simulator, provides DynaMIT with surveillance reports (i.e., sensor counts) of simulated "real world" traffic flows. Just as it would be in a real-world scenario, DynaMIT uses the surveillance report to perform consistent demand estimations and to generate

[6] The k-shortest path is an extension of the shortest path routing algorithm on a road network. When there are impedance on the shortest path between a pair of nodes, other different paths are computed. K is the number of ordered list of available alternatives.

[7] According to [138], under equilibrium conditions, traffic arranges itself in congested networks such that all used routes between an origin-destination pair have equal and minimum costs, while all unused routes have greater or equal costs. Wardrop [138] assumes that travelers know the travel times on all routes and are willing to select the shortest travel time path (static assignment models). However, the dynamic and stochastic nature of traffic makes these assumptions problematic in real world situations. Dynamic equilibrium assignments take the time-varying flows (resistance on the way) into consideration.

unbiased guidance predictions. These guidance forecasts are relayed to MITSIM for dissemination to simulated drivers. The results of the MITSIM simulation are representative of what would occur in reality, and any relevant measures of effectiveness available in the MITSIM reporting capabilities can be used as a basis for an ATIS evaluation.

VISSIM [16], a discrete, stochastic, time step based microscopic model with driver-vehicle-units as single entities has also been used to assess the benefits from ATIS. It employs a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements. The VISSIM modeling environment supports programming of external freeway control systems and other ITS-logic and functionality with a high degree of detail. This includes simulation of road-user responses and behavior to the displayed VSL and usage for evaluation and development of more effective control systems. By upgrading PTV VISSIM with the VisVAP add-on, traffic-actuated signal controls and traffic management systems can easily be implemented by means of flow charts and tested in a safe but realistic simulation environment.

Chowdhury, et al. [144] agreed that microscopic simulation models can be used to evaluate traffic management strategies in real time before a course of action is recommended. However, the problem is that the strategies would have to be evaluated in real time. This might not be computationally feasible for large-scale networks and complex simulation models. To address this problem, two artificial intelligence (AI): paradigms—support vector regression (SVR) and case-based reasoning (CBR) were presented as an alternative to simulation models as a decision support tool.

### 3.3.2 Applications

Varying results from simulation studies on the benefits of ATIS have been reported. Jayakrshnan [137] reported results from a study in Anaheim, California using DYNASMART with the CONTRAM assignment model. A system-wide benefits of up to 10% reduction in average travel time for all vehicles, with benefits for both equipped and unequipped vehicles increasing as market penetration increases (until a penetration of 50% when many drivers receive information, reroute and as a consequence results in congestion on the alternative routes) was reported.

Florian [142] using his developed framework (with DynaMIT and MITSIM) evaluated ATIS. The main inferences drawn were that the provision of dynamic route guidance can simultaneously benefit the individual performance of drivers, both guided and unguided, as well as the system performance of existing transportation infrastructure. First, the provision of predictive ATIS is sensitive to demand characteristics on a given network. In the low demand scenario, the simple network performance was improved by a maximum 28% of total travel time at 100% ATIS market penetration, while the maximum benefit in the high demand scenario was only 12% at 50% ATIS market penetration. Second, the results confirmed the presence of overreaction in the high demand scenario, but not in the low demand scenario. Third, the results showed that the provision of consistent, predictive ATIS can reduce travel times for both unguided and guided drivers, with the guided drivers enjoying most of the benefits. Finally, the results confirmed that unguided drivers also experience benefits in terms of trip reliability. However, the study showed that the provision of poor guidance can significantly deteriorate network performance.

Nissan [145] also used the micro-simulation model, VISSIM, to evaluate the VSL system on a segment of the E4 motorway in Stockholm, Sweden. To operate the Stockholm VSL system in VISSIM, logic similar to its operation was defined and applied using VisVAP. The results from the simulation study indicated that driver compliance is an important factor and VSL performance quickly deteriorates as compliance rate drops. Hence, VSL should be implemented as mandatory instead of advisory. In addition, mandatory VSL can be effective both under incident and moderately congested conditions.

According to [122], traffic network simulation models have been used in London, Southampton, Toulouse, and Turin to predict the impact of VSL on travel time, travel distance, and other network performance indicators. The method required assumptions to be made for driver route choice both for the reference case (no VSL information) and the VSL information case. From the study, in the reference case, traffic was assigned according to user equilibrium principles. In the VSL information case, it was assumed that all relevant drivers (defined as those drivers who travel past VSL information and intend to travel to the destination referred to by the VSL) follow VLS guidance. In general, the deployment of VSL to inform drivers of traffic conditions was found to have proved successful in terms of improving network travel times.

Chowdhury, et al. [144] demonstrated the feasibility of his proposed AI approaches with prototype SVR and CBR systems, and estimates were compared with those from a comprehensive microscopic simulation model. In most cases, SVR and CBR models accurately predicted the likely travel time savings as determined by the simulation model, but SVR performance appears to be superior to that of the CBR. Results of statistical analyses indicated that differences between the simulation model and the SVR estimates were not statistically significant at a 95% confidence level, whereas differences between the CBR and the simulation model were. Another statistical test showed that SVR prediction errors were less than the CBR errors. Specifically, prototype SVR and CBR decision support tools were developed and used to evaluate the likely impacts of implementing diversion strategies in response to incidents on a highway network in Anderson, South Carolina. The performances of the two prototypes were then evaluated by a comparison of their predictions of traffic conditions with those obtained from VISSIM. Although the prototype systems' predictions were comparable to those obtained by simulation, their run times were only fractions of the time required by the simulation model. Moreover, SVR performance were superior to that of CBR for most cases considered.

*Traffic simulation is an important tool for design, planning, and subsequently monitoring the effectiveness of ATIS. A disadvantage of traffic simulation studies is that they have to be calibrated with a huge number of parameters in different traffic conditions and environment. It is also, only as good as its assumptions used in developing the model.*

## 3.4 Summary of Literature and Research Gaps

Existing methods, for analyzing the quality of ATIS, have been discussed and their limitations highlighted in this chapter. Providers offer a variety of traffic information content through different media, and drivers and commuters also have different preferences for receiving the information. These studies agree to the fact that ATIS has the potential to reduce traffic congestion on links and entire road networks. However, the information provided must be **accurate**, **reliable**, and **timely** in order to boost driver and commuter confidence.

In the state-of-the-art VSL evaluations (e.g., [48, 146]), the analysis do not differentiate between the different features of VSL systems, particularly, its ability to automatically detect incident before issuing an appropriate warning or otherwise and how these are related. Again, the quality levels of the systems are not graded.

Traditionally, in assessing the efficiency of VSL systems to smooth traffic, standard deviation of speed has been used [82, 145, 147]. The query this dissertation deals with is whether absolute standard deviations of speeds should be used in evaluating speed differentials.

Huber, et al. [148] acknowledged that existing methods for evaluating the quality of RTTI have not taken the limitations of the inherited protocols in the information broadcasting into consideration. For instance, RTTI providers broadcast speed information for a defined segment per time. Therefore, using the continuous GT to assess the "discrete" RTTI messages may not be fair, at least, from the viewpoint of the provider. Huber, et al., [148] considered this limitation arising from the segmentation by introducing the technical ground truth (TGT). The TGT discretizes the continuous GT to assume the grids of the individual segments and each segment is represented with the harmonic average speed within it. The problem with using the harmonic average speed is that some incidents will go undetected if drivers are still able to travel at higher speeds at uncongested portions of the segment. The lower speeds, which are critical in determining incidents, will be concealed in the whole calculation. Instead, the minimum speed within the segment should be used.

Studies (e.g., [146, 149]) have found that significant proportion of situations where VSL systems fail to detect incidents (i.e., missed detections) occur at queue tails and therefore recommend the need for a model to predict congestion. This is what optimal control strategies intend to address. This control approach takes advantage of the availability of historical data, real-time traffic data on a link or networks to also make predictions in the traffic information they broadcast. Superimposition of the areas of the GT traffic situation and the broadcast information without taking into consideration, periods during which the controller might have predicted and issued correctly congestion warnings, amounts to penalizing the provider for doing something which is beneficial to ATIS. In the comparison between VSL and RTTI in this dissertation, this is considered.

# Chapter 4

# Study Location and Description of Data

Freeways in Germany (popularly referred to as autobahn) do not have a universal speed limit. VSL systems are, therefore, considered as a legal means to cause drivers to reduce speed when necessary. According to [150], about 10% of freeways in Germany are equipped with control systems that can show variable speed limits. RTTI can also be accessed for most parts of the freeways. In this chapter, the study location, traffic information systems at the site, and the data, used in the case study later on in this dissertation, are described.

## 4.1 Study Location

The study location (between the points marked "A" and "B" in Figure 4.1) is a six-lane freeway of the autobahn A99 near Munich, Germany. It forms part of the city of Munich's "outer-ring-road" network. The southbound direction (i.e., Salzburg direction), is used for the field test. It is approximately 33.5 km long roadway. The number of lanes ranges from two to four, but predominately a three-lane roadway. The freeway also has a temporary hard shoulder lane running. During peak hours of the day or when its use become necessary, the temporal hard shoulder lane is opened to traffic. There are eleven on-ramps and twelve off-ramps carefully designed to allow vehicles enter or exit the freeway. The schematic diagram of the site is shown in Figure 4.2. Other details on the diagram will be explained in the next section.

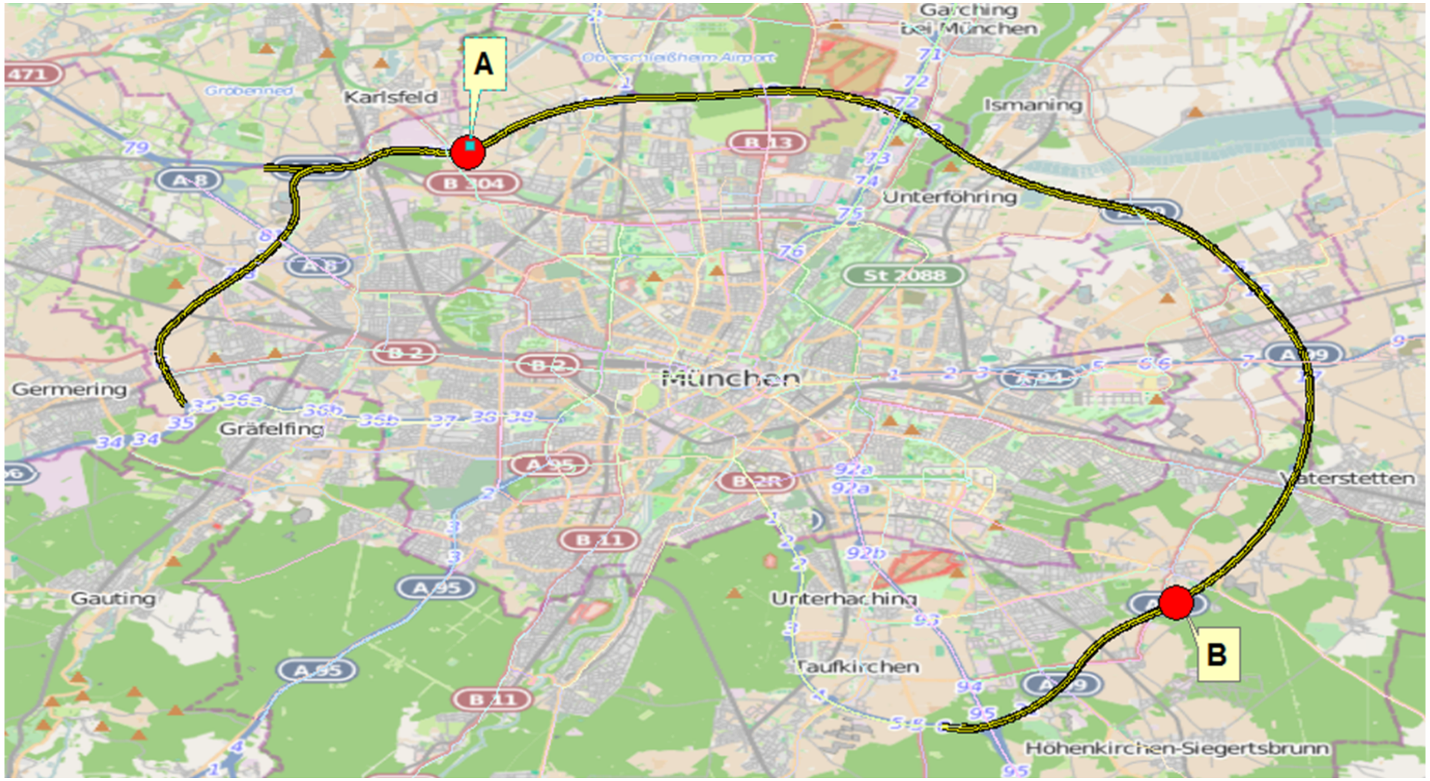



Figure 4.1: Site map - Autobahn A99 near Munich, Germany

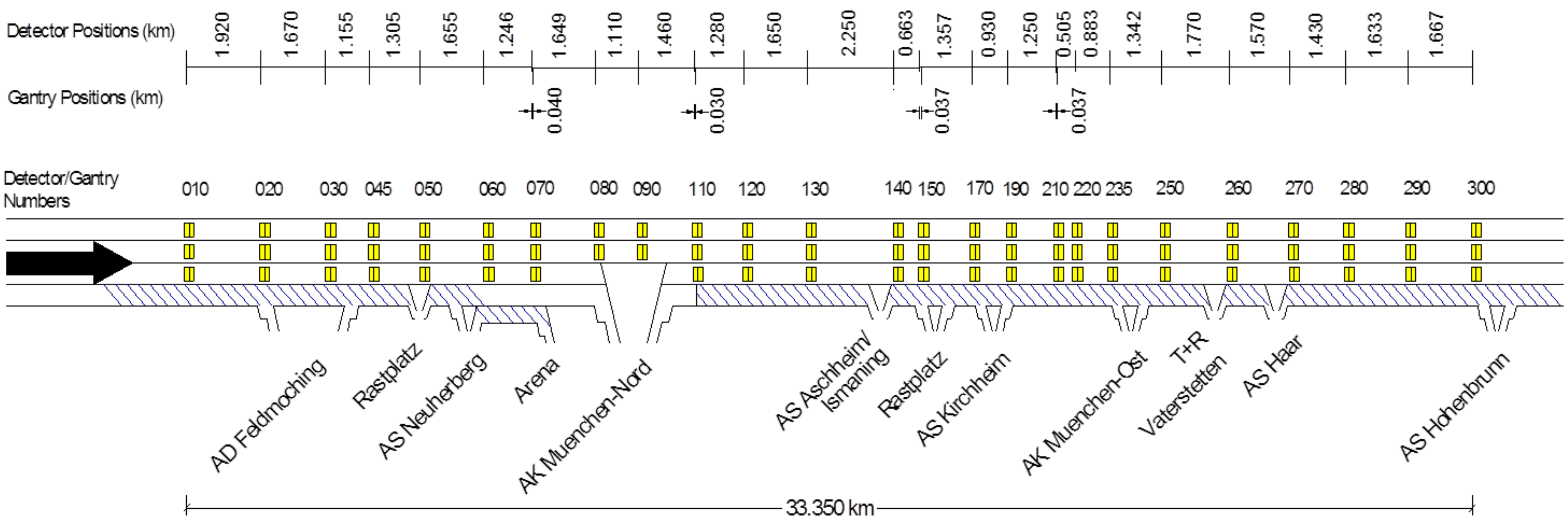



Figure 4.2: Schematic diagram - Autobahn A99 near Munich, Germany

### 4.1.1 VSL Facility

The road corridor is equipped with a VSL system with dual inductive loop detectors in each of the driving lanes (including the temporary hard shoulder lane) that collect information on vehicle speed, flow, occupancy, and so on. In total, there are 25 detectors with spacing between consecutive stations ranging from 505 m to 2250 m with an average spacing of 1390 m. The VSL facility, displays its information (i.e., speed limits, warning messages, etc.) on overhead gantries placed across the carriageway. When the hard shoulder lane is permitted for use, it is communicated to drivers by the overhead gantries. There are a total of 24 gantries spaced along the freeway with distances between consecutive gantries ranging from 700 m to 2250 m. Average spacing between gantries is 1450 m. With the exception of four which indicated slight differences in their positions, the gantries are placed above the detectors (i.e., at the same locations). The loop detector stations and VSL gantry positions for measuring traffic variables and displaying speed limits/message signs respectively, are labeled in Figure 4.2 according to the naming format used by the Autobahn Direktion Südbayern (South Bavarian Highway Authority). Autobahn Direktion Südbayern is the body responsible for the administration, control, development, and maintenance of the freeway and its facilities. Remote weather information system, which record weather information, is also found along the freeway.

The VSL at the study site is a dynamic system and is turned on when triggered by high traffic flow or adverse weather conditions. It implements heuristic control approach [48] and pursue warning and harmonization strategies in managing traffic. The system, also implements dynamic truck restriction strategy. The dynamic truck restriction prohibits trucks from overtaking during peak periods in order to smooth traffic. Figure 4.3 shows the percentage of time that the VSL system was active by hour of day for June, 27 2012. During substantial parts of night-time (21:00 - 6:00 Hrs), almost all or several of the VSL signs are off. During daytime, particularly at rush hour periods when traffic needs to be harmonized, the system is mostly on. Its use is reduced during non-rush hours. When the system is off, drivers are allowed to travel as fast as they would like (no speed limit).

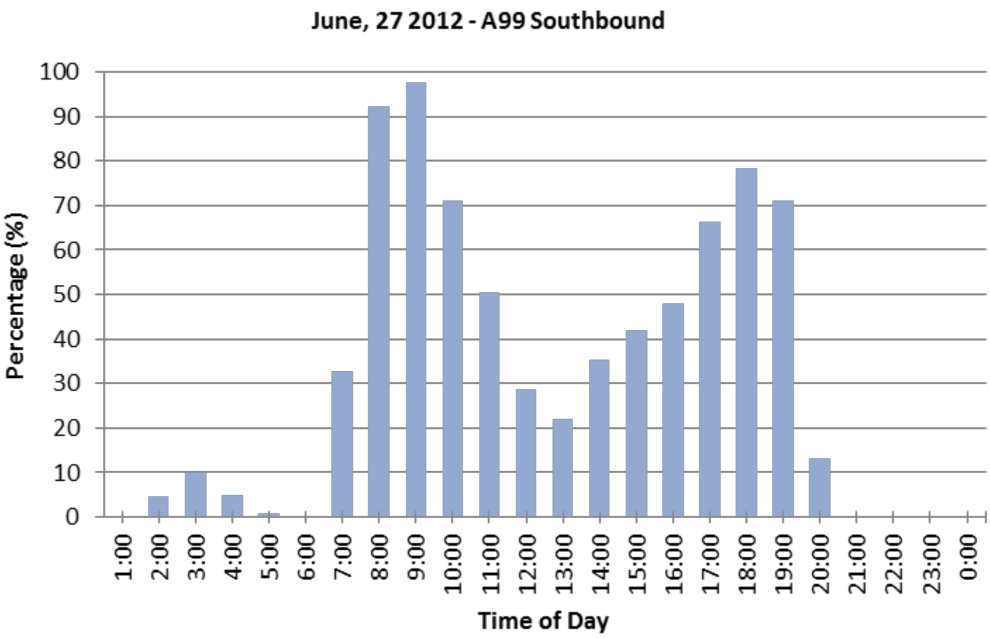



Figure 4.3: Percent time VSL system is active.

### 4.1.2 RTTI Facility

On this same road corridor under consideration, drivers are able to access RTTI on their navigation devices. The service provider, whose data is used for this research work, transmits information per TMC segment. There are 13 TMC points (i.e., 12 TMC segments) for which traffic information is broadcast. Spacing between TMC locations range from 887 m to 5593 m with an average spacing of 2780 m. It is worth mentioning that although the start of the first TMC location (RTTI 1) extends upstream of the first VSL position (MQ 10), in the analysis, RTTI kilometer post started at the same location at which VSL information is available. Again, the end of the last TMC location (RTTI 13) was truncated to match the last VSL gantry position. This was done to enable comparison of the two information sources.

## 4.2 Data Description and Preparation

Data from the VSL system at the site for the year 2012 for the four month period, April – July were available for the study. RTTI data, for the same time period, were also available. The nature and type of data used in this study are described below.

### 4.2.1 VSL Data

Archived VSL data were obtained from the Autobahn Direktion Südbayern. The data procured consisted of:

- Archived stationary detector data (which included time-average speeds, standard deviation of speeds, and traffic volume),
- Logged variable speed limits, and
- Logged dynamic messages displayed to drivers.

Each of the above listed category of data were contained in a separate folder. For each detector station and gantry location, there was a file containing the information collected for a day. The identification of respective information for sensor stations and gantries were possible as the files were named according to the naming system shown in Figure 4.2. The data were stored in extensible markup language (XML)-format. Therefore, codes were written in MATLAB to extract them. All data types were aggregated at 1-minute resolution. For traffic flow data, the vehicles were segregated by length, classified into cars and trucks. Dynamic messages and speed limits displayed to drivers are as shown in Table 4.1.

Table 4.1: Dynamic messages and speed limits displayed by the VSL system on autobahn A99

| No. | **Messages** |
|---|---|
| 1 | Congestion |
| 2 | Potential congestion |
| 3 | No overtaking by trucks |
| 4 | Danger ahead (e.g., snow, skidding, narrowed road, and construction work) |
| 5 | Error (in case of malfunction) |
| No. | **Speed Limits (km/h)** |
| 1 | 60 |
| 2 | 80 |
| 3 | 100 |
| 4 | 120 |

### 4.2.2 RTTI Data

The RTTI data, obtained from a private provider, consisted of speeds broadcast to consumers. The data, just like the VSL information, were aggregated at 1-minute interval. For each TMC segment, there was a file containing speed displayed to drivers for the entire 24-hours of the day. The RTTI data were stored as text (.txt) files. Consequently, MATLAB was used to extract the data into a spreadsheet program.

There was the need to relate the positions of the TMC locations to the VSL gantry positions. The chainages (kilometer posts) of the detector stations and gantry locations along the freeway were available as well as their coordinates. But for RTTI, only the coordinates of the TMC locations were known. Therefore, the coordinates of the detectors and the TMC locations were plotted in ArcGIS, and the kilometer post of the TMCs determined by measuring the distance in relation to the known detector stations' kilometer post. Figure 4.4 shows a plot of the coordinates of the detector stations (black dots) and TMC locations (red dots). With this, the VSL and RTTI data were brought under the same dimension and could, thus, be compared. The positions of the TMC points and the VSL gantries, and the distances between them are also illustrated in Figure 4.5.

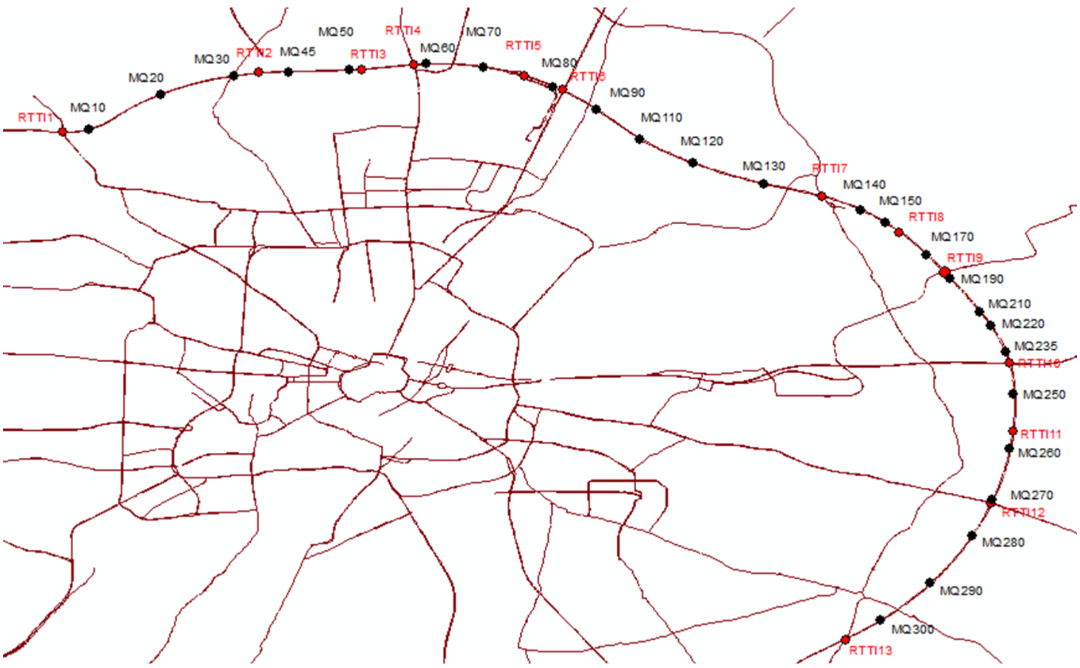



Figure 4.4: Plot of detector stations and TMC locations.

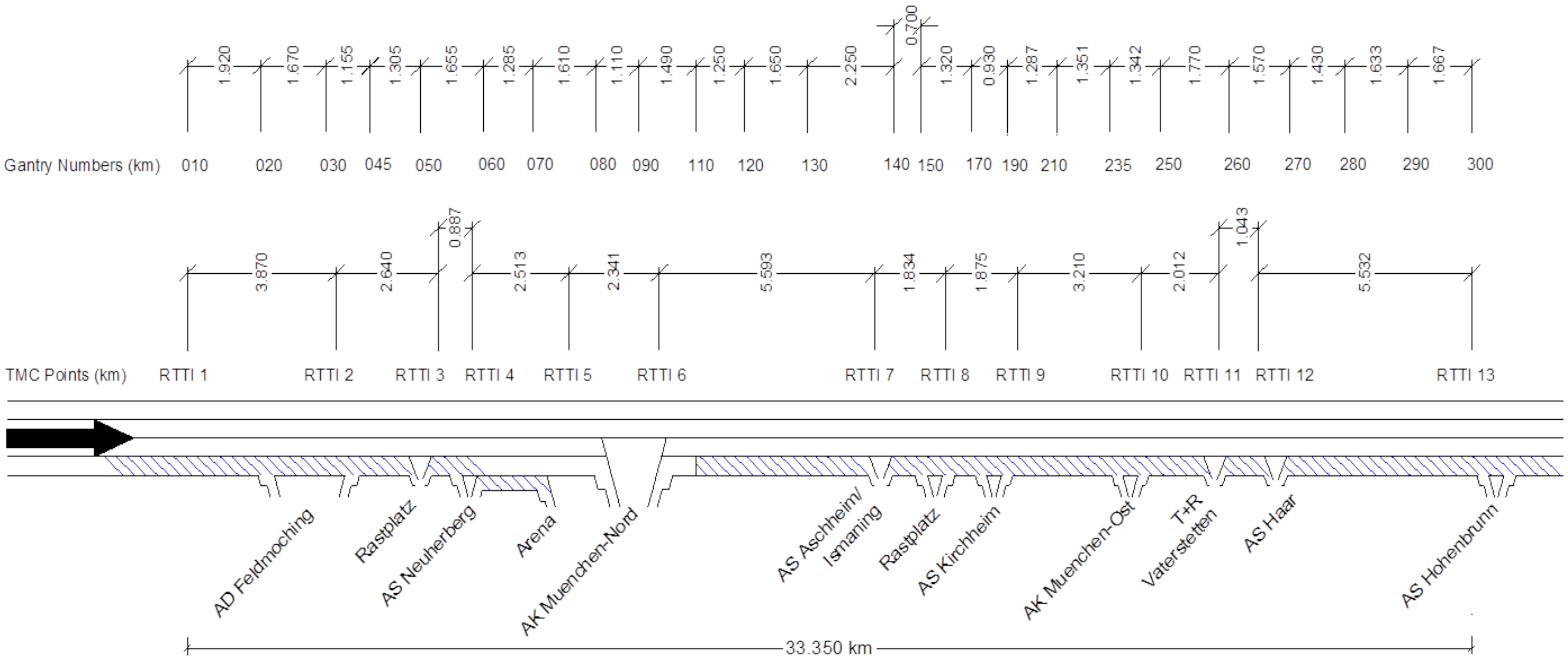



Figure 4.5: Distances between VSL gantry positions and TMC points

# Chapter 5

# Research Methodology for Assessing VSL Systems

Different VSL systems have been used all over the world to manage traffic. Specific objectives for implementation may vary from one country to the other and from one road corridor to the next. Whereas some dynamic speed limits are advisory, others are mandatory. There exist VSL installations which are fully automated whilst some require human operators. Some systems deploy only message signs which provide warnings of hazardous conditions, but others only variable speed limits. In many cases, variable speed signs are used in combination with dynamic messages. Additional information such as constructional works, travel time, and route guidance may also be displayed by a VSL system.

A dynamic VSL system is expected to firstly detect and alert the control of any changes in the traffic environment. The incident detection component of VSL systems, which automatically raises alarms of changes in the traffic environment, is a very important aspect of the system in dealing with the random nature of incidents on freeways. After an incident is detected, a corresponding warning message and/or speed must be displayed. The algorithm for warnings relies on alarms from incident detection. Excellent automatic incident detection may result in efficient warnings. Conversely, incorrect automatic incident detection will lead to false warning alarms. As a result, it is prudent to assess the quality of the system in incident detection before proceeding to the warning capability. This will make it easier to ascertain where a problem is coming from in the system. A feature of VSL systems is also to smooth traffic (i.e., harmonization). This control system aims to systematically dampen speeds to stabilize and smooth traffic, usually based on the prevailing measured traffic flow, speed, density, or weather condition. Reduced speed differences ensure that vehicles travel with a more consistent speed, decrease lane changing maneuvers which lead to fewer traffic conflicts, decreases noise, and reduces environmental pollution.

Methods for evaluating three features of VSL systems, namely:

- incident detection,
- warning, and
- harmonization

are presented in this chapter. As VSL systems may be implemented with different control strategies, an approach for assessing the different features of the system independently was adopted. In this way, systems with different control strategies can be assessed.

## 5.1 Incident Detection

The flow chart for evaluating the VSL system's capability in incident detection is illustrated by Figure 5.1. Since it is practically impossible to install stationary detectors along the entire road length and record information continuously, a reconstruction of the traffic state is required. Archived inductive loop speed data were used for this purpose.

### 5.1.1 Reconstruction of the Traffic State - Ground Truth (GT) Generation

The objective of the reconstruction of the traffic state is to estimate speed values for all locations along the freeway and for all times to represent the actual traffic state (ground truth). Simple orthogonal or isotropic interpolation is not suited for modeling traffic data as it is unable to explain adequately the conventional principles of traffic flow and as a result leads to artifacts [75]. Therefore, the adaptive smoothing method (ASM) proposed by Treiber & Helbing [75], which takes the characteristic propagation velocities observed in free and congested traffic into account, was used for the GT generation. In free flowing traffic, information travels downstream whilst in congested conditions, information travels upstream.

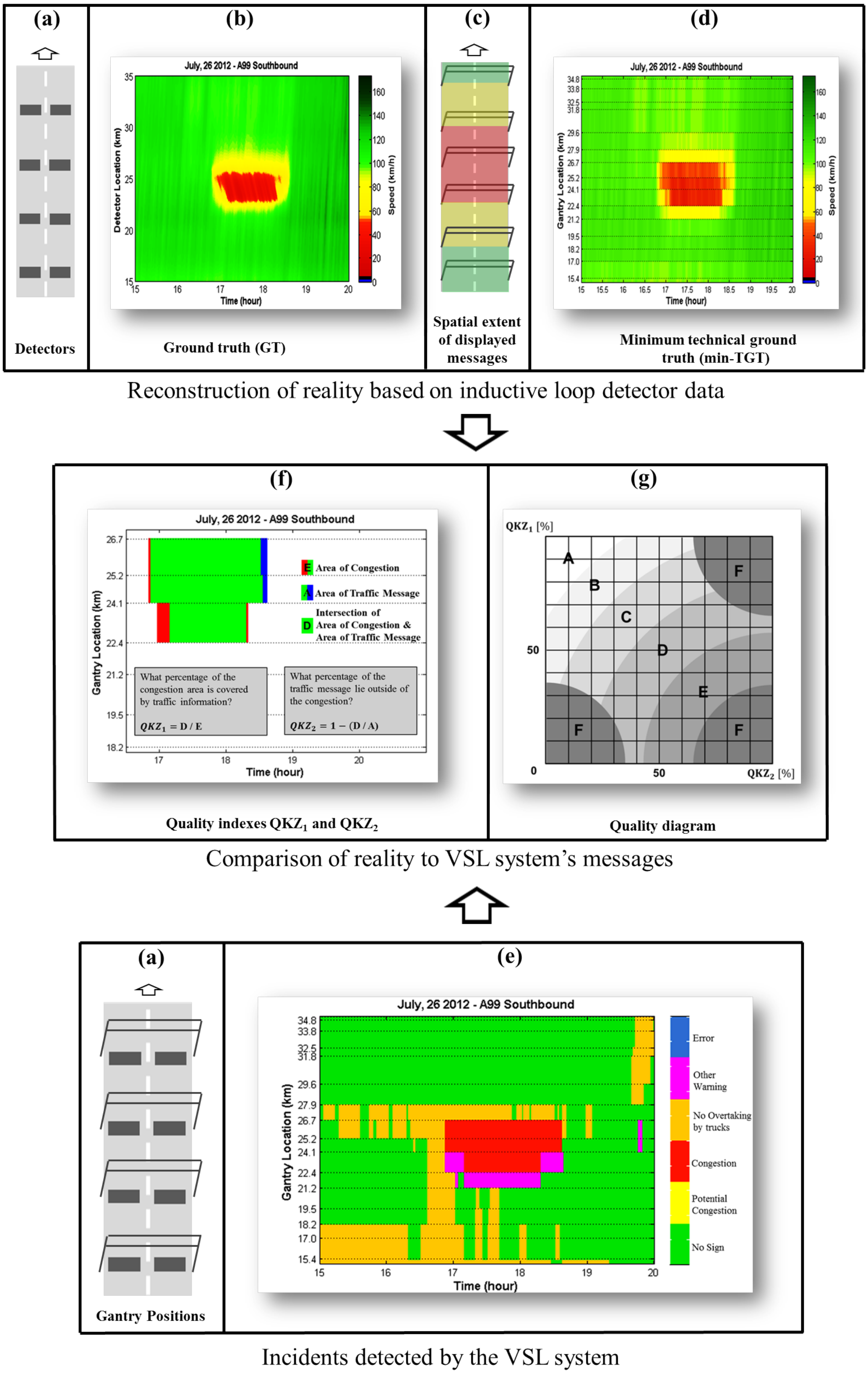



Figure 5.1: Flowchart for assessing incident detection.

The advantage of using the ASM for the reconstruction process is that it is robust and requires only a few parameters [75, 151]. The ASM was established on the conventional isotropic interpolation and both are explained below.

### Isotropic Interpolation

According to [75], supposing $u_i$ is the average aggregated speed measured by $detector_i$ at location $x_i$ at time $t_i$ along a freeway segment, the continuous speed function $U(x,t)$ is a discrete convolution with a kernel $\phi_0$ that includes all data points $i$. The filter is given by Equation 5.1:

$$U(x,t) = \frac{1}{N(x,t)} \sum_i \phi_0(x - x_i, t - t_i) u_i \tag{5.1}$$

The isotropic convolution kernel used is the symmetric exponential (Equation 5.2).

$$\phi_0(x - x_i, t - t_i) = exp\left( -\frac{|x - x_i|}{\sigma} - \frac{|t - t_i|}{\tau} \right) \tag{5.2}$$

The normalization of the weighting function in Equation 5.1 is defined as in Equation 5.3.

$$N(x,t) = \sum_i \phi_0(x - x_i, t - t_i) \tag{5.3}$$

The problem with the isotropic interpolation is that it assumes all traffic conditions are the same, which, in reality, is not the case.

### Adaptive Smoothing Method (ASM)

The ASM takes into account the information propagating velocities in both congested and free flowing conditions. The kernels of the anisotropic filter representing free flowing $\phi_{free}$ and congested $\phi_{cong}$ situations are defined as in Equation 5.4 and Equation 5.5, respectively.

$$\phi_{free}(x - x_i, t - t_i) = exp\left( -\frac{|x - x_i|}{\sigma} - \frac{\left| t - t_i - \frac{x - x_i}{c_{free}} \right|}{\tau} \right) \tag{5.4}$$

$$\phi_{cong}(x - x_i, t - t_i) = exp\left(-\frac{|x - x_i|}{\sigma} - \frac{\left|t - t_i - \frac{x - x_i}{c_{cong}}\right|}{\tau}\right) \tag{5.5}$$

where $c_{free}$ and $c_{cong}$ are characteristic velocities in free and congested situations, respectively.

The GT is therefore obtained by bringing together the two speed fields and weighting them non-linearly depending on the traffic situation (see Equation 5.6).

$$U(x,t) = w(x,t)U_{cong}(x,t) + [1 - w(x,t)]U_{free}(x,t) \tag{5.6}$$

The adaptive weighting factor is defined as in Equation 5.7.

$$w(x,t) = \frac{1}{2}\left[1 + tahn\left(\frac{U_c - U^*}{\Delta U}\right)\right] \tag{5.7}$$

where $U_c$ represents the crossover from free to congested traffic, $\Delta U$ is the width of the transition period and $U^*(x,y) = min(U_{free}, U_{cong})$. A factor of approximately one indicates congested situation and zero indicates free flowing situation.

Applying the ASM as described above is time consuming since it takes some time to compute the traffic state of a few kilometers. Of course, this is not much of a problem now because of the availability of computers with high-level computational capacity. Nevertheless, a faster method of implementing the ASM called the fast Fourier transform (FFT) as described in [151] has been used. The FFT has the advantage of increasing computation time by a factor of up to 100 while the filter quality is nearly preserved with only negligible discretization errors. The application of the ASM for the GT reconstruction results in a high resolution spatio-temporal speed function. Figure 5.2 is an example of a speed-contour plot generated by applying the ASM on inductive loop detector data. The speeds were estimated at 25 m intervals in every 10 s. These figures can even be lowered further, but it will have an impact on the computation time. The red areas indicate, in space-time dimensions, lower traveling speeds whiles green regions show higher speeds. It is evident from the figure that congested areas are smoothed upstream whereas free flowing regions are smoothed downstream in relation to the direction of travel (from chainage 15 km to 35 km in this example). In this way, the characteristic propagation velocities in free and congested traffic states are considered in the traffic state modeling.

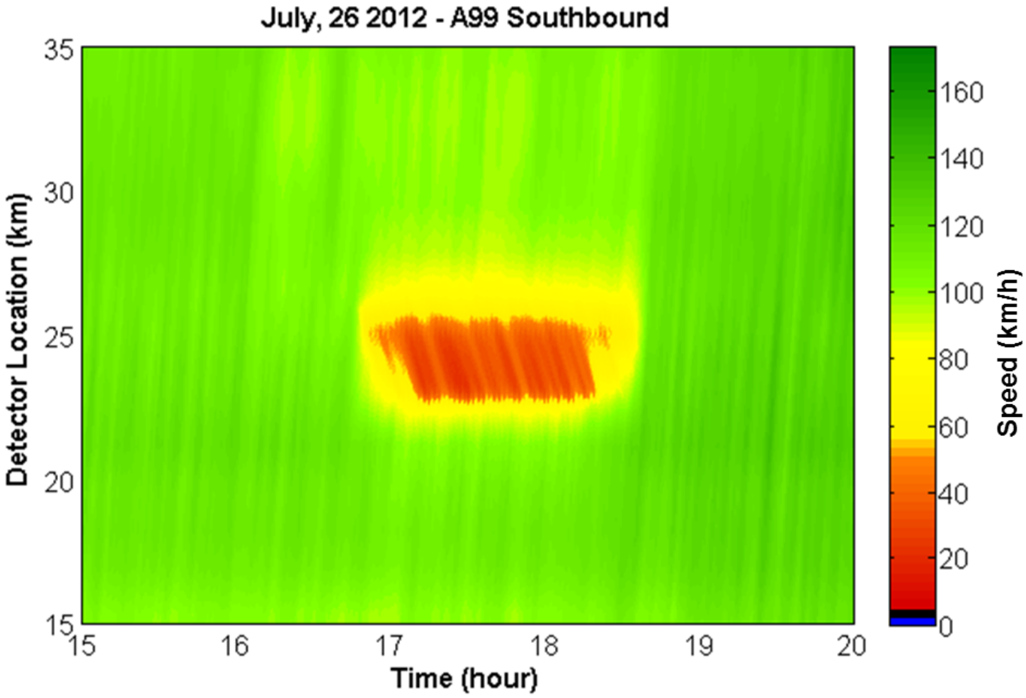



Figure 5.2: Reconstruction of ground truth speed

### 5.1.2 Generating the Minimum Technical Ground Truth (Min-TGT) Speeds

Figure 5.1(a-d) present the concept behind the generation of the Min-TGT. The VSL and message information are displayed on gantries installed along the road at specific locations. The information provided on a gantry represents the entire downstream segment until the next gantry is reached where a different message may be displayed or the restriction is lifted (see illustration in Figure 5.3). Unfortunately, the reconstructed GT is continuous whilst the information is discrete (bounded by the gantry locations). In order to make comparison possible, the continuous GT is discretized spatially to assume the same grid as the positions of the gantries. Temporally, it is discretized to match the time interval at which the system aggregates information, that is, 1-minute. Each cell is then represented with the minimum speed value (from the ASM computation bounded by the VSL gantry grids) to form the Min-TGT matrix. Using the average speed to represent the segment will mean speeds, lower than the average, which constitute harmful situations will not be detected. The aim is to identify congested regions between the gantries in order to warn drivers upstream of the situation. This is determined by checking whether the minimum detected speed ($V_{min}$) lies below a certain threshold ($V_{crit}$). If $V_{min} < V_{crit}$, the segment is classified as congestion region. Figure 5.4 shows a discretized GT for the traffic situation presented in Figure 5.2. The dotted horizontal lines indicate the position of the gantries. From the two figures (i.e., Figure 5.2 & Figure 5.4), it is observed that the discretized GT compares quite closely to the continuous GT.

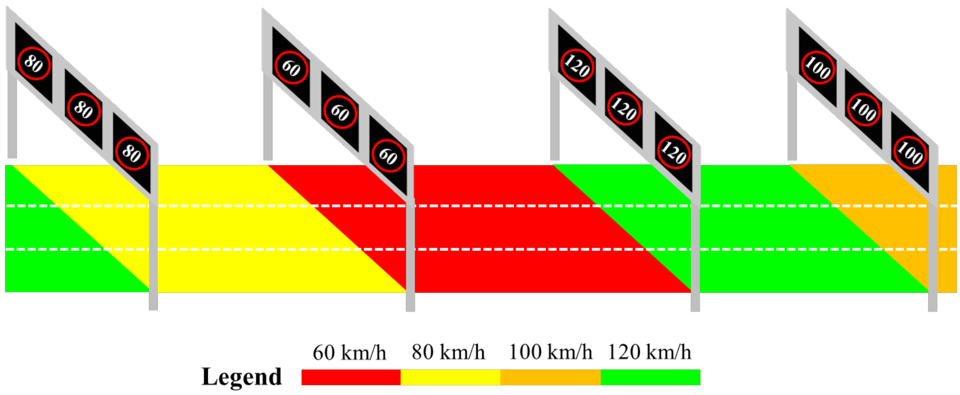



Figure 5.3: Spatial extent of displayed VSL

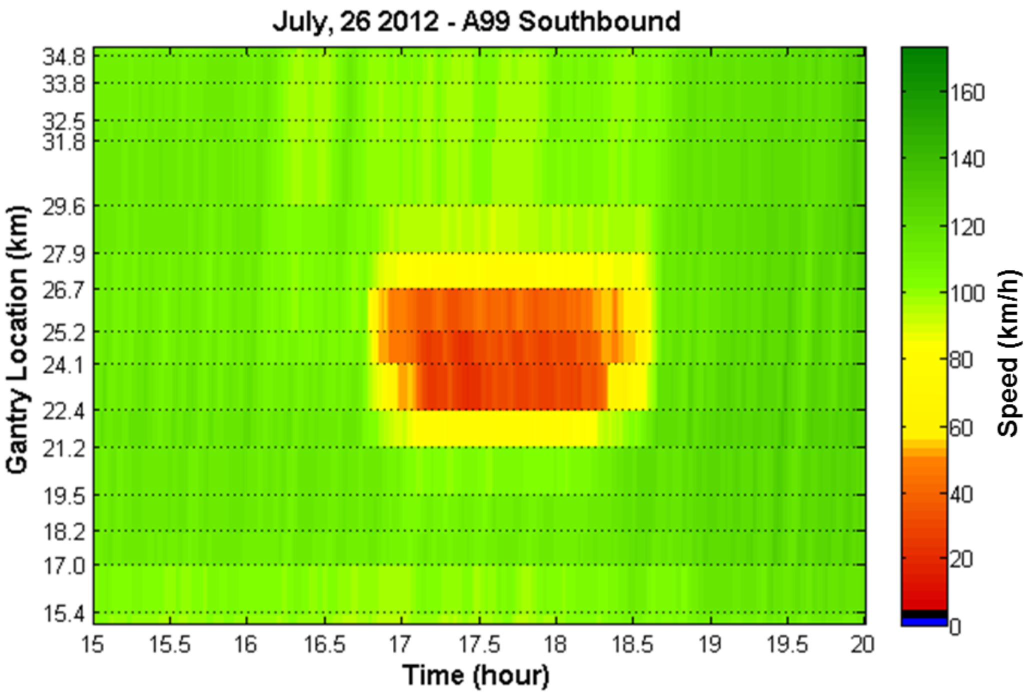



Figure 5.4: Discretization of ground truth speed

### 5.1.3 Representation of Driver Information

Logged data, from the VSL system for the same period at which detector speed data are being studied, are required as input. A spatial-temporal matrix containing all information displayed to drivers is produced from the message data. As mentioned, spatially, the limits of the information broadcast are controlled by the positions of the gantries. Since the system is dynamic, the time ranges for which a speed limit or messages are displayed determine the temporal extent. Messages displayed by the system include congestion, potential congestion, no overtaking by trucks, and so on. Figure 5.5 shows a graphical representation of message signs which were displayed to drivers. In free flowing traffic, when there is no incident, "no sign" is displayed as represented by color green in the figure. "Other warning signs" included constructional works, snow, skidding and narrowed road. The system at the study location implements truck restriction strategy to smooth traffic in dense traffic. This is indicated in the figure by "no overtaking by trucks." Whenever the system malfunctions, it is represented by "error" although this condition did not appear in this example.

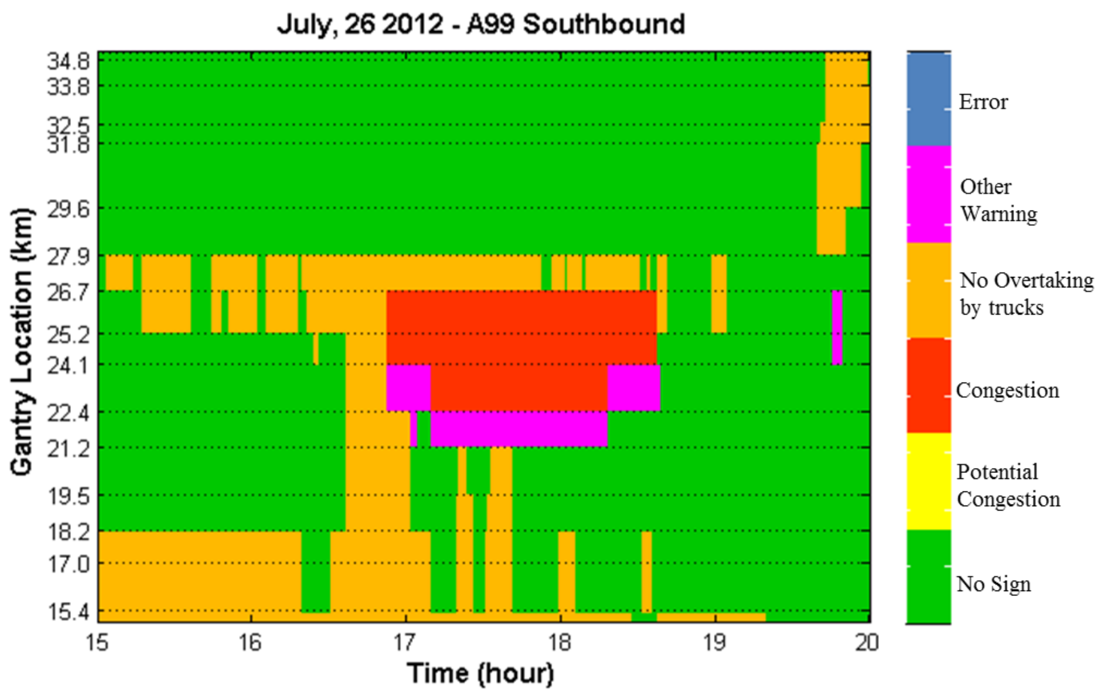



Figure 5.5: Space-time representation of messages

### 5.1.4 Message Signs versus Min-TGT

The idea of the generation of the Min-TGT was to make it possible to compare and superimpose it to the message signs. A defined threshold for incidents is required at this point for the comparison. One possibility is to use the system's defined threshold. However, it is worthy to note that a message may be displayed not based solely on speed (i.e., speed threshold) but also on other factors, for example, weather. Instead of the system's interior threshold, also a speed threshold which is assumed to reasonably describe dangerous situations can be used. The incident areas, which are identified on the basis of the aforementioned threshold are compared to the message matrix. For example, if the sign "congestion" is displayed and the defined threshold for congestion is 60 km/h, a Min-TGT $<$ 60 km/h will signify a match whiles Min-TGT $\geq$ 60 km/h will mean a mismatch. Looking at the Min-TGT (Figure 5.4) and the message signs (Figure 5.5) on their nominal value, it can be said that, at least for congested regions, the two figures largely match to each other in time and in space. The subsequent sections will subject this observation to further analysis.

### 5.1.5 Grading of Incident Detection – QKZ Method

After matching the matrices, it is necessary to determine the VSL's global capability in incident detection quantitatively. Specifically, grades are used here to assess the quality levels. The so-called QKZ method proposed by Bogenberger [128] was used for this purpose.

The method was initially used to assess the quality of RTTI. It is adapted, in this research, for VSL systems. The QKZ method compares the space-time area of the actual traffic state to the space-time area of traffic information (which in this case is the information displayed by the VSL system). From the superimposition of the discretized GT and representation of messages displayed by the system, two indexes, $QKZ_1$ which is the detection rate and $QKZ_2$ which is the false alarm rate, are calculated. The percentage of incident areas which is covered by the VSL messages (i.e., detection rate), and the percentage of VSL messages which lies outside of the congestion areas (i.e., false alarm rate) are computed and entered on a quality diagram for the grading of the VSL system in incident detection. Example of the superimposition of the discretized GT and VSL congestion message areas and the method for calculating the indexes are illustrated in Figure 5.6.

Spatio-temporal regions where there was no congestion and no traffic information were excluded from the analysis. This comprised of a huge proportion of all traffic situations and including them would have concealed the visibility of missed detections and false alarms which require attention. The quality scale is again shown in Figure 5.7. For more details on the QKZ method, the reader is referred to section 3.2.2. By going through this procedure, the VSL system is assessed and graded from the system's perspective.

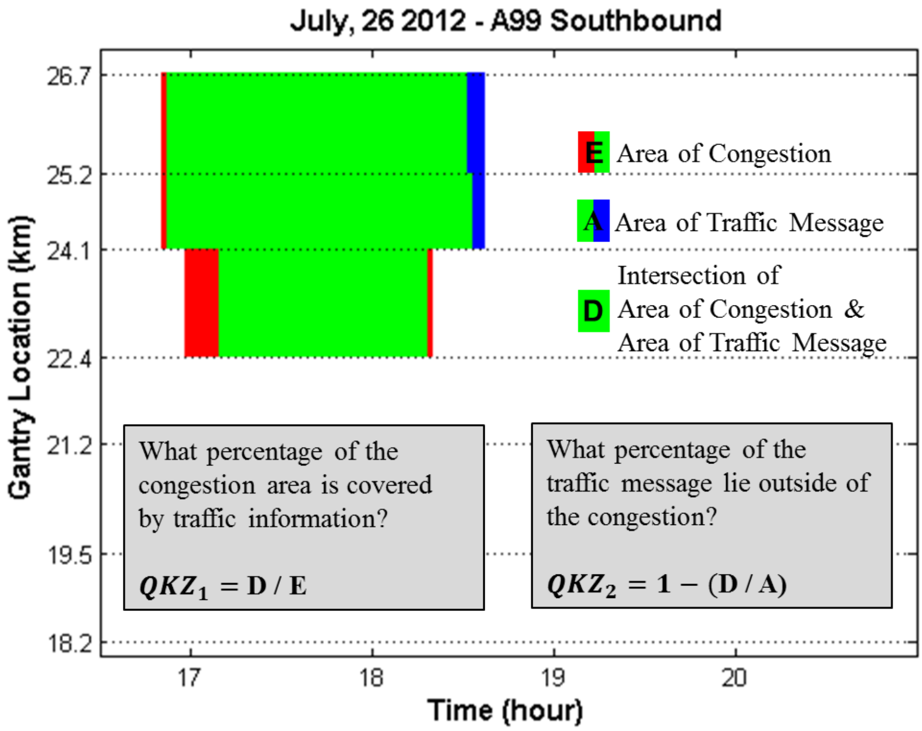



Figure 5.6: Estimation of $QKZ_1$ and $QKZ_2$

## 5.2 Warning Capability of VSL Systems

The framework for evaluating the warning capabilities of VSL systems is as shown by Figure 5.8. The goal is to assess the VSL system during a certain time period $T$ for a certain road corridor $X$ from a driver's perspective. To achieve this, the ASM is applied to reconstruct the GT to cover the considered spatio-temporal region $X \times T$ as described in section 5.1.1. The GT, as a representation of the real traffic situation, is used as reference to the experienced messages to establish whether a driver gets appropriate and timely warning corresponding to the traffic situation. Note that, in this context, the GT is preferred to the Min-TGT because we want

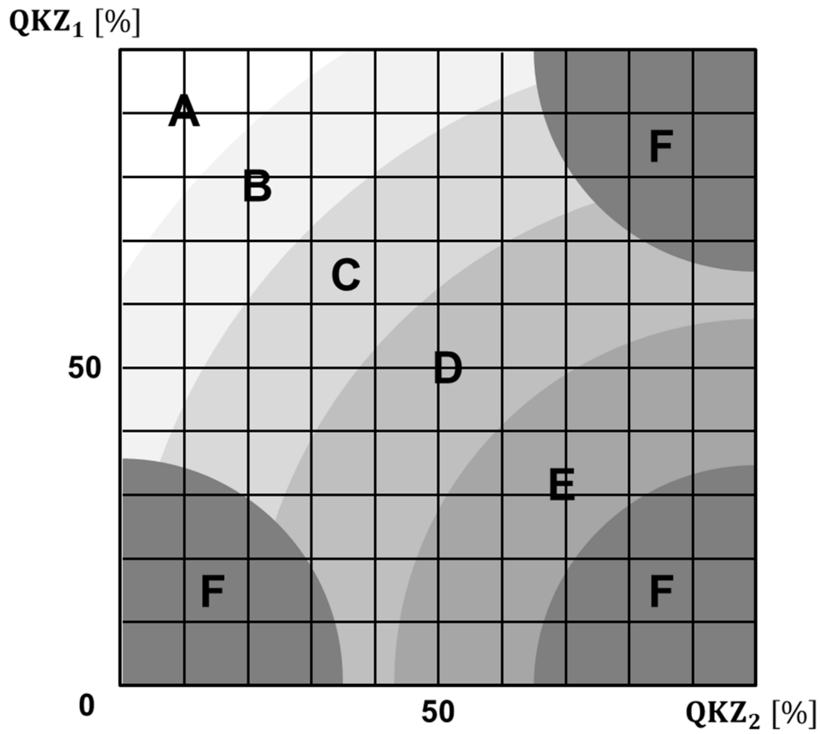



Figure 5.7: QKZ quality diagram

to get as close to reality as possible. Since the driver's perspective is considered, trajectories based on the GT are computed to simulate vehicles and their behavior.

### 5.2.1 Generation of Virtual Trajectories

The generation of virtual trajectories is done to help determine the information drivers encounter as they traverse the route. Reconstruction of trajectories from inductive loop detector data has been extensively researched [148, 152–156]. Estimating accurate vehicle trajectories is dependent on how the underlying space-time speed map through which the vehicles are assumed to travel are reconstructed. The filtered speed-based (FSB) trajectory method, proposed by [152] and modified by [148], is used for the trajectory generation. This is possible as the ASM results in a high density space-time grid based speed function from which trajectories can be computed by simply solving ordinary differential equations. The high resolution grid is to ensure a good approximation of the real traffic situation as experienced by a driver. These trajectories are generated at a specified starting time interval (e.g., every five minutes) to cover the whole spatio-temporal region. The time interval should be chosen in such a way that it is able to

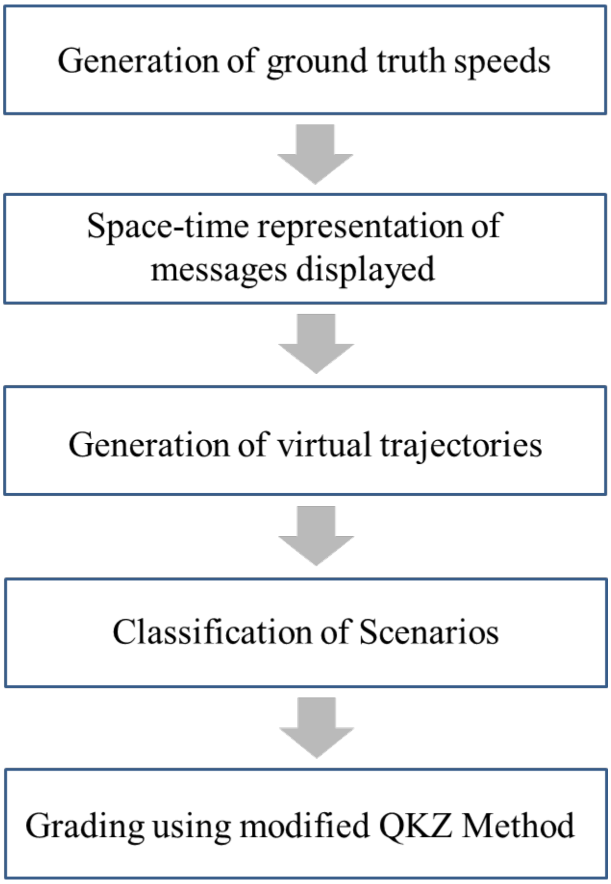



Figure 5.8: Framework for evaluating warning capability of VSL

capture all changes in traffic condition [146]. Whenever a trajectory leaves the spatio-temporal region $X \times T$, free flowing traffic condition is assumed. From this, the GT speed $U_{(X,T)}$ at any location $X$ at a time $T$ used by a vehicle which follows the given trajectory, that is, the speed profile, is known. Figure 5.9 shows a graph of VSL gantry positions (x-axis) against the GT speed (y-axis), by a vehicle following a trajectory at a starting time of 17:00 hours on the autobahn A99, near Munich for July, 26 2012. The time used by the vehicle to pass over one gantry to the other (passing time) is also indicated. The example in Figure 5.10 illustrates virtual trajectories, generated using the modified FSB method, plotted on an ASM contour plot from which they were estimated. The blue line in Figure 5.10 indicates the trajectory which profile was shown in Figure 5.9. From the figure, it is realized that, relatively, within congested regions, the virtual vehicles take longer times to travel (gradual slopes) as against the shorter times in non-congested regions (steep slopes).

Already, the driver information matrix has been created (subsection 5.1.3). The generated trajectories are then also superimposed on the spatio-temporal matrix representing the displayed VSL messages. Figure 5.11 also shows virtual trajectories plotted into a space-time representation of message signs. By doing this, the message experienced by a vehicle at any particular gantry and time is determined.

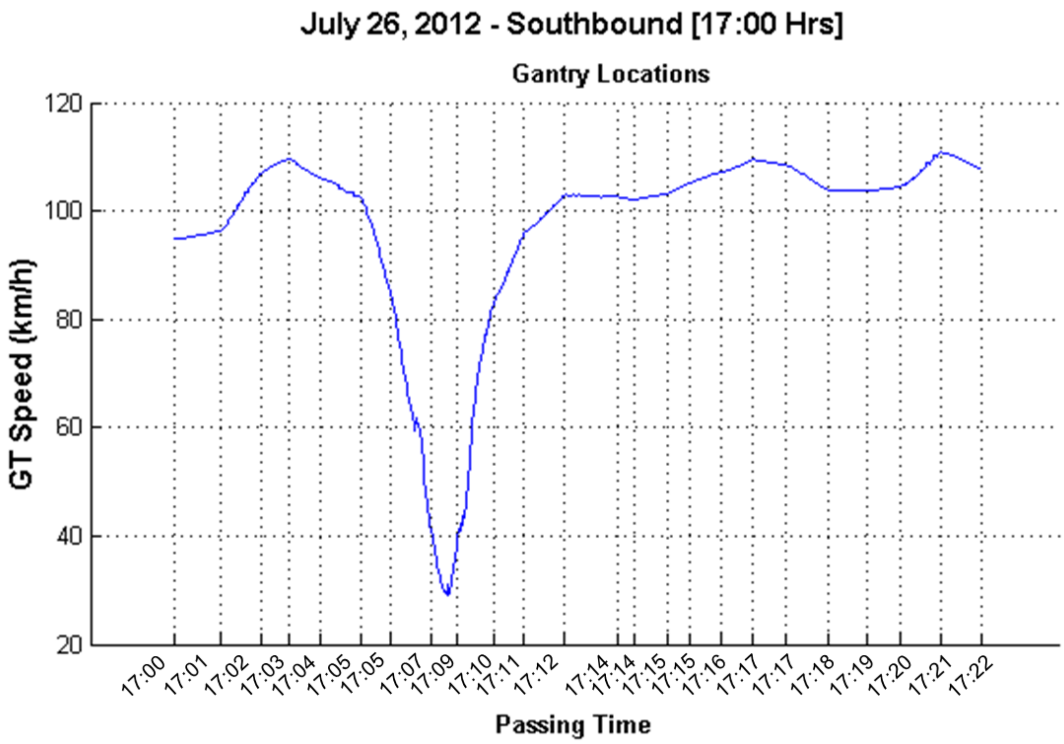



Figure 5.9: Speed profile of a generated trajectory

### 5.2.2 Grading of Warning Messages

A major reason for VSL systems is to enhance traffic safety by giving warning messages. These warning messages should be given in advance to allow adequate time for drivers to perceive, identify, decide, and undertake the necessary maneuvers [157]. On the contrary, messages placed too far in advance of the traffic condition are also not good as drivers might tend to forget the warning or assume a false alarm. Based on recommendations from [157] and engineering judgment, a warning distance of between 300 m and 3500 m from the tail of incident is considered appropriate to allow for adequate reaction time on freeways.

Now, each of these generated trajectories is considered separately. To enable the comparison, a defined threshold for incidents and their spatial locations (particularly tail of the incident) need to be determined. Here, congestion is

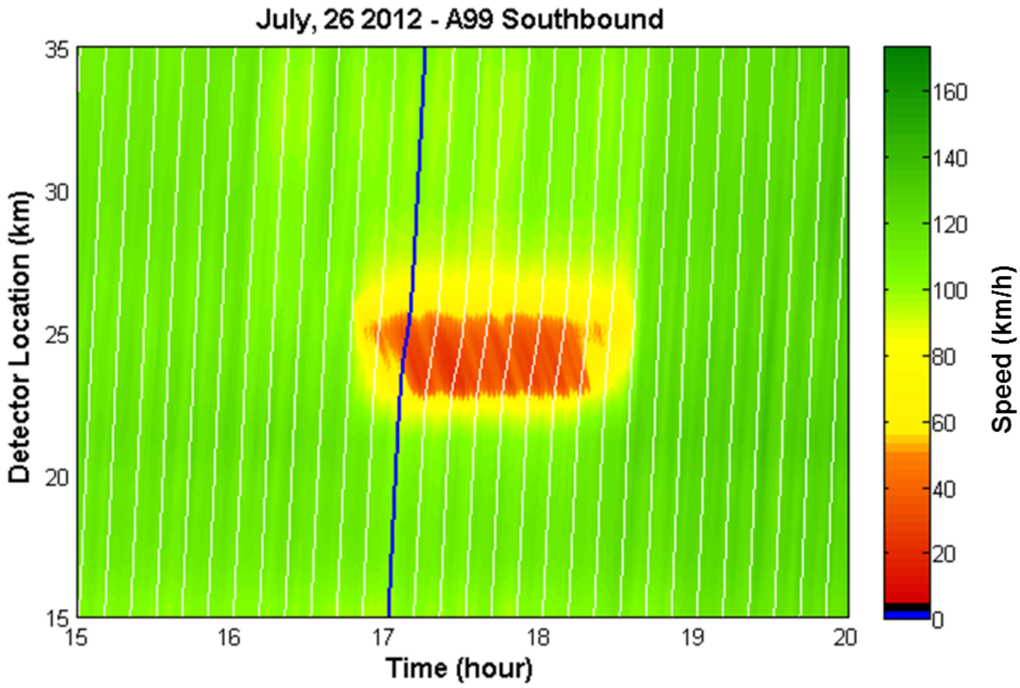



Figure 5.10: Trajectories plotted on an ASM speed contour map

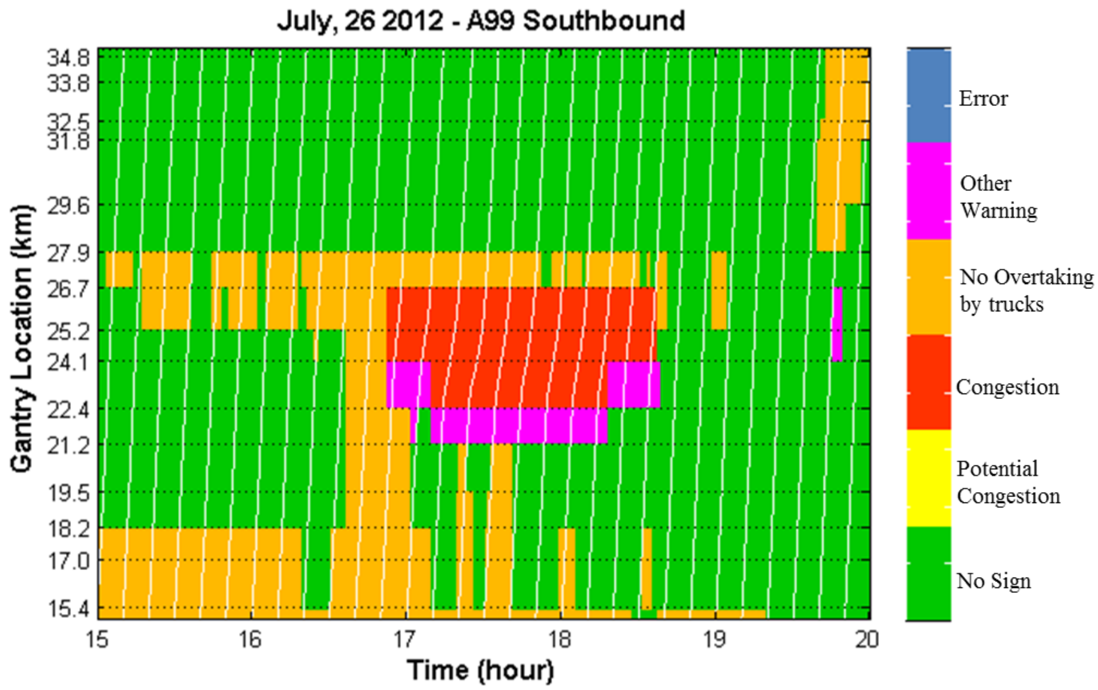



Figure 5.11: Trajectories superimposed on space-time representation of messages

defined as all parts of the considered trajectory with speeds less than the defined threshold $V_{crit}$ for congestion. A vehicle path is then followed to determine whether appropriate and timely warning messages would be displayed by each of the VSL gantries to warn a driver. To accomplish this, different scenarios (explained in the next section) are introduced and a check is then done on which of these warning scenarios were encountered along the trajectory.

### 5.2.3 Scenarios for Warning Messages

Ten (10) scenarios have been identified as possible encounters by a vehicle on a trajectory. These scenarios have again been broadly categorized into three types based on the distance ($d$) of the individual VSL gantries to the queue tail of the next downstream congestion as follows:

- **Type A (Long distance warnings):** Conditions in which the distance of the warning to the next downstream queue tail is greater than 3500 m.
- **Type B (Short distance warnings):** The warning message is within a distance of 3500 m to the tail of the next downstream congestion.
- **Type C (Warning in congestion areas):** A vehicle is in congestion when passing a gantry.

In assessing messages displayed by gantries in scenarios of types A and C, all gantries passed by a vehicle are assessed individually. However, in scenario of type B, all gantries upstream of the congestion (i.e., within a distance of 3500 m from the congestion tail) are considered and rated as a whole. This is because every message displayed within the recommended distance of posting advance warning is considered crucial and any inconsistency or error may have an influence on safety. Subsequently, weightings ($w_i$) are awarded to each of the different scenarios depending on its influence on road traffic safety. The grading of the warning efficiency is done in the context of the QKZ method. However, it is important to note that by considering a set of scenarios and their corresponding weightings, the message area $A$, the congestion area $E$ and the intersection area $D$ are not given directly as in the case of incident detection. But, it is possible to associate each of the scenarios with one of these areas. For example, if a correct congestion warning has been experienced before congestion is reached, this can be interpreted as "detection" and assigned to area $D$. Moreover, if no message is displayed although an incident exists, this can be interpreted as "missed detection" and assigned to the set $E$, but not $A$ (i.e., $E$ without $A$, written as $E \setminus A$). Finally, if a message is displayed when there is no corresponding incident, this is interpreted as "false alarm" and assigned to the set $A$, but not $E$ (i.e., $A$ without $E$, written as $A \setminus E$).

A detailed explanation of the different scenarios and their weightings is given below. All scenarios are also visualized in Figure 5.12. The thick blue lines show the vehicle trajectories moving from the bottom to the top, dashed horizontal lines show VSL gantry locations and red areas mark congestion. The triangles indicate whether or not a congestion warning is displayed when the vehicle passes the gantry.

### Type A - Long Distance Warnings ($d > 3500$ m)

*Scenario A.1 - Warning in Free Flowing Traffic ($d > 5000$ m)*: In this situation, drivers following the considered virtual vehicle trajectory receive a warning message which does not correspond to the traffic situation ahead of them. This leaves the drivers in a state of dilemma after driving for some time without meeting the supposed incident. Conditions like this may lead to increased travel time and disrespect for displayed messages in the future. It represents the negative extreme situation in free flowing traffic and receives a full weighting of 1.

*Scenario A.2 - Warning distance too far ($3500 \leqslant d \leqslant 5000$ m)*: A notification of a downstream congestion is given but the warning is placed too far in advance of the traffic condition. This scenario is considered as negative, but should be weighted differently from a situation where there is no warning. A linear weighting between zero and one is suggested for distances between 3500 m and 5000 m with distance 5000 m attracting the highest weight of 1 and 3500 m attracting a weight of 0.

*Scenario A.3 - No Warning in Free Flowing Traffic ($d > 3500$ m)*: This represents an ideal situation in free flowing traffic. Any warning displayed under this circumstance would cause unnecessary delay to motorists. In the context of the QKZ method, this situation is not considered as it cannot be assigned to the areas $A$, $D$, or $E$. It also ensures that the system does not get evaluated when it is deactivated and there is nothing to warn.

### Type B - Short Distance Warnings ($d \leqslant 3500$ m)

*Scenario B.1 – No Warning at Last Gantry before Congestion*: The system fails to react to changes in traffic conditions and therefore no sign is displayed at the first upstream gantry of a congested region. Drivers are not appropriately warned and are taken by surprise of the downstream incident. This condition has a serious consequence on safety as it may lead to crashes. It represents the negative extreme case in congested situations and should get a weight of 1.

*Scenario B.2 – Warning at last gantry before Congestion (*$300 \leqslant d \leqslant 3500$ *m) but no Warning at the Next Upstream Gantry*: Situations in which there is congestion at a downstream location, the driver receives timely advance warning message from the system and can react accordingly to reduce traveling speed in order to avoid crashes. This represents an ideal case in congestion situations and attracts the full weight of 1.

*Scenario B.3 - Warning at Last Gantry before Congestion but no Warning at Next Upstream Gantry (*$0 \leqslant d < 300$ *m)*: A situation in which an incident is detected at a downstream location, a warning is given but the distance from the warning to the tail of the queue is not enough to allow adequate reaction time. Although there was detection, the warning does not bring enough benefit to motorists. This should be weighted lower than in scenario B.1 (where the driver was not warned at all). Consequently, a linear weighting between zero and one is suggested for distances between 100 m to 300 m with a distance of 300 m attracting the lowest weight. Messages displayed at a distance of less than 100 m are considered as scenario B.1 (no warning) and thus receives a weighting of 1.

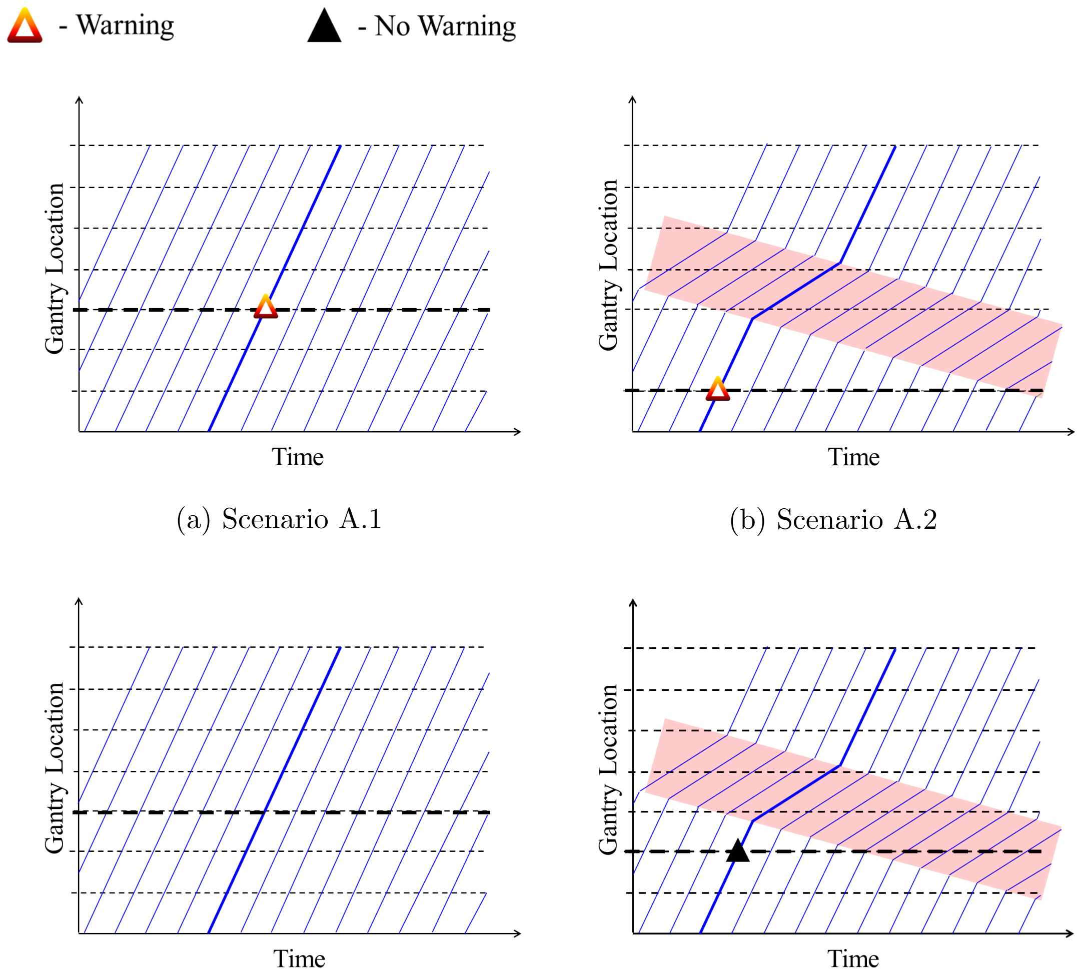
*Scenario B.4 - At Least the Last Two Upstream Gantries before Congestion Display Warnings*: In this situation, the driver receives enough advance warning and can therefore react to forestall a crash. It is rewarded with a full weight of 1.

*Scenario B.5 - Interrupted Warning Sequence*: This scenario has the potential to increase the tendency of drivers disobeying displayed messages. For example, an incident is detected downstream of a segment, the fourth upstream gantry displays a warning message, the third does not but the second and first do. Looking at the sequence, a driver might disregard the displayed messages as a result of inconsistency and this will have serious issues on safety. Here, a weight of 1 should be awarded. If the first gantry upstream of the congestion does not display a warning, scenario B.5 reduces to scenario B.1.

### Type C - Warnings in Congestion Areas

*Scenario C.1 – Warning in Congestion*: In this condition, the driver gets a correct warning message (positive scenario). However, the motorist is already caught up in traffic and cannot travel at his/her desired speed. There is no safety benefit from this situation though the credibility of the system is enhanced. The contribution of this scenario in estimating the overall quality of the system should be lower than in scenarios B.2 or B.4. A weight of 0.5 is suggested.

*Scenario C.2 – No Warning in Congestion*: – Although no sign is displayed in this situation, this scenario has no effect on traffic safety. The driver can only travel with the speed of the vehicles on the wave. This condition should be weighted lower than scenario B.1 when there was no warning at the queue tail. A weight of 0.5 is proposed.

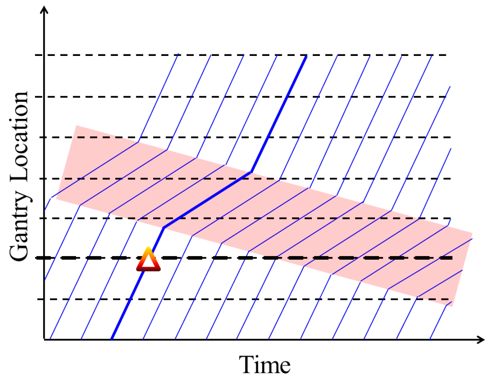



(a) Scenario A.1

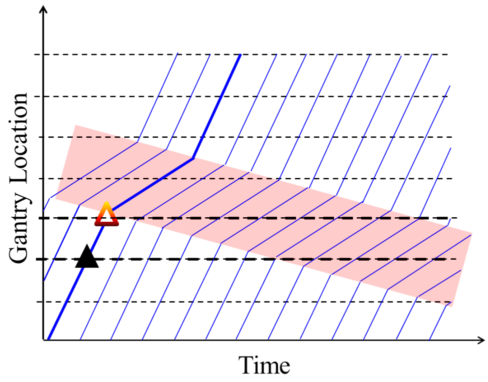
(b) Scenario A.2

(c) Scenario A.3

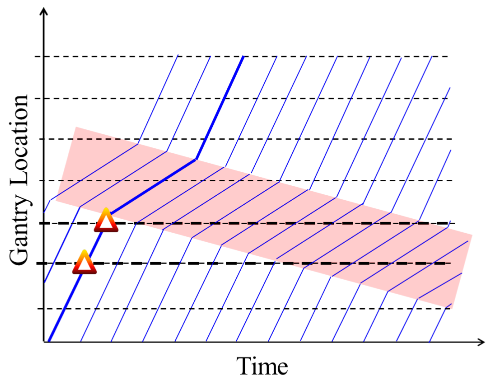
(d) Scenario B.1



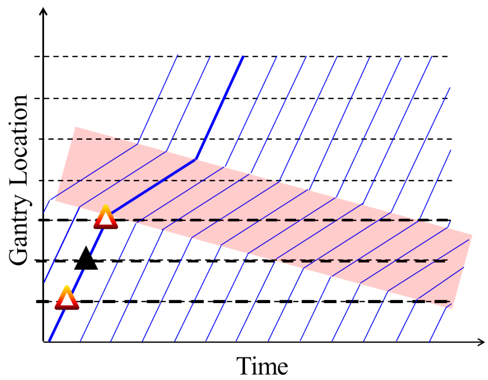

(e) Scenario B.2



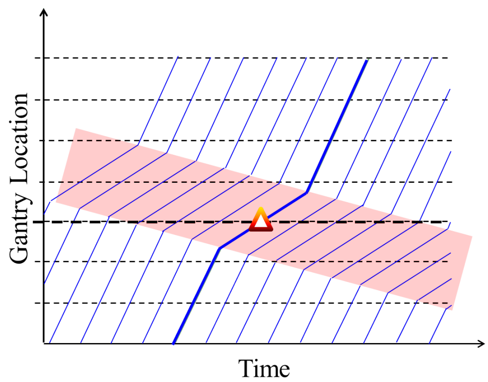

(f) Scenario B.3



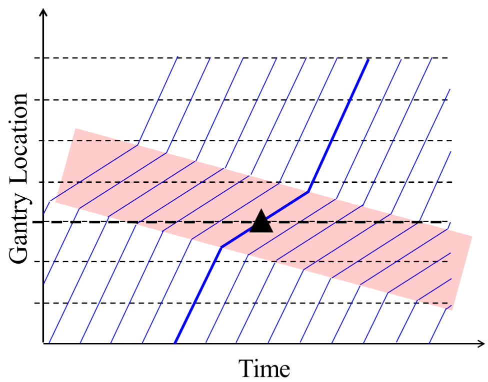

(g) Scenario B.4




(h) Scenario B.5




(i) Scenario C.1




(j) Scenario C.2

Figure 5.12: Scenarios encountered by vehicle on trajectory

### Assigning Scenarios

The basic algorithm for the identification of the different warning scenarios is shown in Figure 5.13. A vehicle on a trajectory receives traffic information from a gantry. The algorithm then checks the distance between the currently reached gantry and the tail of the queue of the next downstream congestion. It then assigns the experience of a driver to one of the three broadly classified scenario types. If the distance ($d$) from the gantry to the queue tail is greater than the maximum distance accepted to give advance warning ($d_{max}$), which is taken as 3500 m in this study, the scenario is assigned to type A. When $d$ is greater than zero but within $d_{max}$, the algorithm assigns the scenario to type B. The scenario type is designated as C if it does not meet any of the conditions above (i.e., the presently considered gantry is within congestion). Next, the condition encountered is assigned to one of the ten scenario types.

For scenarios of type A, if the presently encountered gantry displays congestion warning ($C_{message} == true$), and $d$ is greater than the distance beyond which giving a warning is considered as too long (false alarm warning distance denoted as $d_{false}$), it is assigned to scenario type A.1. A distance of 5000 m have been used for $d_{false}$ and the reason for its introduction is as follows. It was contemplated that having a **sudden switch** from warning distance being adequate (300 to 3500 m) to warning distance being too long will not be fair to the grading system. For instance, a driver receiving a warning at a distance of 3500 m will be considered as having received adequate warning whilst a driver receiving an information at a distance of 3501 m is taken as having received a long distant warning. Therefore, a linear weighting is adopted for distances between $d_{max}$ and $d_{false}$. That is, if a motorist gets a warning at a distance of say 3600 m, although it is taken as a negative scenario (i.e., false alarm), it is weighted lower than a driver who receives a warning at 4900 m. These encounters are assigned to scenario A.2. On the other hand, if no congestion situation exists at distances greater than $d_{max}$ and the considered gantry does not display any congestion information, it is assigned to A.3.

In a case that the scenario is designated as type B, as mentioned, all gantries within the distance $d$ are considered and assessed as a unit. Whenever the last of all the gantries downstream (i.e., first gantry upstream of the congestion, denoted as $VSLG_{end}$) displays no warning ($C_{message} == false$), it is assigned to scenario type B.1. However, if $C_{message}$ is true and the distance from $VSLG_{end}$ to the congestion tail, denoted as $d_{gan}$, is greater than the minimum acceptable distance for warning ($d_{min}$), they are assigned to scenario type B.2. A value of 300 m is used for $d_{min}$. Whenever, the distance $d_{gan}$ is less than $d_{min}$, and the next upstream gantry (i.e., second gantry from the congestion ($VSLG_{end-1}$)) does not display a warning, it is taken as a missed detection. Again, in order to avoid **sudden switch** from adequate warning distance to no warning, a linear weighting is employed for distances between where there is a warning, but considered to be too short ($d_{low}$, pegged at 100 m) and therefore has little significance. Although this is considered as a negative situation, distances closer to $d_{min}$ are weighted lower than distances closer to $d_{low}$. The algorithm assigns this scenario type to B.3. Whenever the last two gantries display congestion warning, it is assigned to B.4. The scenario type is assigned to B.5 if the currently considered gantry shows a message and any of the downstream gantries within $d$ do not display a message. Note that B.5 can be assigned in parallel to one of scenarios B.2, B.3, or B.4. In this case, two scenarios with separately computed weightings are experienced, increasing also the number of considered scenarios in Equations (5.12) – (5.14) by two.

The assignment of scenarios designated as type C is quite straight forward. If the considered gantry is within congestion and there is congestion message, it is assigned to scenario type C.1 while it is assigned to C.2 when there is no congestion message.

### 5.2.4 Quality Assessment of Warning Capability

The use of the QKZ method in assessing the warning efficiency is to allow a direct comparison to the quality rating according to incident detection. Here again, two quality indexes, $QKZ_1$ and $QKZ_2$ are generated. The formulas are basically the same as in the QKZ-method (see Equation 3.10 and Equation 3.11). As mentioned, the message area $A$, the congestion area $E$, and the intersection area $D$ are not directly given in the different scenarios, but each of these scenarios can be assigned to an area (see Table 5.1 for an overview of the relation between scenarios and areas). Therefore, Equation 3.10 and Equation 3.11 have to be rewritten. For this purpose, the following computations ensue:

$$E = E \backslash D \cup (E \cap D) = E \backslash D \cup D \tag{5.8}$$

```
Initialization:
      i = count of number of gantries between
      displayed message and queue;
      d = distance from current gantry to queue tail;
      d_min = minimal warning distance (300 m);
      d_low = warning distance too low (100 m);
      d_max = maximum warning distance (3500 m);
      d_gan = distance from last gantry before
      congestion to queue tail
      d_false = false alarm distance (5000 m);
      C_message = congestion message at gantry (true if
      there is message; false if there is no message);
      sc_type = scenario type;
      VSLG = VSL gantries within d
      VSLG_(1) = First VSL gantry within d
      VSLG_(end) = Last VSL gantry within d

Scenario Type A
Step 1      if d > d_max
Step 2            if C_message(VSLG_(1)) == true
Step 3                  if d > d_false
Step 4                        sc_type = A.1
Step 5                  else sc_type = A.2;
Step 6                  end if
Step 7            else sc_type = A.3;
Step 8            end if

Scenario Type B
Step 9      else if d > 0
Step 10           if C_message(VSLG_(end)) == false
Step 11                 sc_type = B.1;

Step 12           if C_message(VSLG_(end)) == true
Step 13                 if d_gan ≥ d_min
Step 14                       sc_type = B.2;
Step 15                 else if d_gan ≥ d_low
Step 16                       if C_message(VSLG_(end-1)) == false
Step 17                             sc_type = B.3;
Step 18                       else if C_message(VSLG_(end-1)) == true
Step 19                             sc_type = B.4;
Step 20                       end if
Step 21                 end if

Step 22           if any(C_message (VSLG_(1) to VSLG_(end))) == false
Step 23                 sc_type = B.5
Step 24           end if

Scenario Type C
Step 25     else if C_message(VSLG) == true
Step 26           sc_type = C.1;
Step 27     else sc_type = C.2;
Step 28     end if
```

Figure 5.13: Algorithm for assignment of warning scenarios

$$A = A \backslash E \cup (A \cap E) = A \backslash E \cup D \tag{5.9}$$

These formulas result directly from the fact that $D$ is the intersection of $A$ and $E$. By using them, the QKZ-indexes can be computed as

$$QKZ_1 = \frac{D}{E} = \frac{D}{E \backslash D \cup D} \tag{5.10}$$

$$QKZ_2 = 1 - \frac{D}{A} = 1 - \frac{D}{A \backslash E \cup D} \tag{5.11}$$

Considering all generated trajectories, a set of experienced scenarios $S_1, S_2, \ldots, S_N$ with their corresponding weightings $w_i$ are obtained. This set is then used to rate the quality of the VSL system for the time period $T$ and the road corridor $X$. The total number of the different scenarios assigned to areas $D$ (i.e., detection), $A \backslash E$ (i.e., false alarm), and $E \backslash D$ (i.e., missed detection) are computed by summing up all weightings of the different scenarios:

$$D = \sum_{j \leqslant N \ with \ S_j \in \{B.2, B.4, C.1\}} w_j \tag{5.12}$$

$$A \backslash E = \sum_{j \leqslant N \ with \ S_j \in \{A.1, A.2, B.5\}} w_j \tag{5.13}$$

$$E \backslash A = \sum_{j \leqslant N \ with \ S_j \in \{B.1, B.3, C.2\}} w_j \tag{5.14}$$

So far, the warning capability can be computed according to the QKZ-method. But two modifications which are used for the case study have to be mentioned. Firstly, defining congestion solely on critical speed value $V_{crit}$ has the disadvantage that the experienced traffic state can change quickly within a short time interval when following a trajectory. This is always the case if the realized speeds oscillate around $V_{crit}$. Such a situation, as in the case of stop-and-go waves, is critical for a driver and must be avoided. Allowing drivers to accelerate only for them to reduce their speeds in a short duration will not bring any benefit to the system. In such situations, the congested areas are merged. Therefore, an **experienced congestion** is defined as all parts of the considered trajectory where speeds less than a certain value $V_{crit}$ occur in addition to all parts of the trajectory where this speed threshold is surpassed for a short period, that is, if the distance separating the two regions is less than 3500 m. This distance is chosen according to the highest distance for which posting advance warning is assumed to be reasonable. The second modification concerns the determination of the scenarios for the VSL gantries at the start and at the end of the considered road corridor. If congestion is experienced shortly after the start, the first gantry is the only available gantry to provide information. If the congested area is located less than 300 m from the gantry, then scenario B.3 which is a negative scenario would be assigned. This seems not fair. Thus, in this special case, scenario B.2 which represents a correct warning is assigned. For the last gantry in the segment, no evaluation is done. This is because we do not have the benefit of the traffic situation downstream as the position of the last detector is the same as the position of the last gantry.

## 5.3 Harmonization

Harmonization control strategy in VSL systems aims to systematically dampen speeds to stabilize and smooth traffic. Papageorgiou et al. [83] defined speed harmonization or homogenization as:

> *the reduction of speed differences among vehicles (longitudinally) and of mean speed differences among lanes (laterally).*

In this section, two methods for assessing harmonization are proposed. The first approach is an extension of the traditional method of using absolute standard deviation of speed to assess inhomogeneity in the traffic stream as in, for example, [82, 145, 147]. In this study, a different metric is used to measure the deviation in speeds. Furthermore, the inhomogeneity assessment is done in non-congested situations where high flows occur. This is because the application of a VSL system to resolve inhomogeneity is useful only under such circumstances. The second approach uses straightforward measurement by checking the systematic consecutive variation of the displayed speed limits (i.e., consistency). The idea behind this approach is the assumption that proper coordination of displayed speeds should result in harmonized traffic. While the speed differential approach can be used to assess mean speed differences among lanes (lateral speed harmonization), the consistency approach can be used to measure speed differences among vehicles (longitudinal speed harmonization).

Table 5.1: Different scenarios and weights awarded

| No | Description | Area | Weight |
|---|---|---|---|
| | **(A) Long Distance Warnings** ($d > 3500$) | | |
| A.1 | Warning in Free Flowing Traffic ($d > 5000$ m + Warning) | A\E | 1 |
| A.2 | Warning distance too far ($3500 \leqslant d \leqslant 5000$ + Warning) | A\E | Linear |
| A.3 | No Warning in Free Flowing Traffic ($d > 3500$ + No Warning) | - | - |
| | **(B) Short Distance Warnings** ($d \leqslant 3500$) | | |
| B.1 | No Warning at Last Gantry before Congestion | E\A | 1 |
| B.2 | Warning at last gantry before Congestion ($300 \leqslant d \leqslant 3500$) | D | 1 |
| B.3 | Warning at Last Gantry ($100 \leqslant d < 300$) before Congestion but no Warning at Next Upstream Gantry | E\A | Linear |
| B.4 | At Least the Last Two Upstream Gantries before Congestion Display Warnings | D | 1 |
| B.5 | Interrupted Warning Sequence | A\E | 1 |
| | **(C) Warnings in Congestion Areas** | | |
| C.1 | Warning in Congestion | D | 0.5 |
| C.2 | No Warning in Congestion | E\A | 0.5 |

Again, the consistency approach could be employed as a quick check in determining the potential of VSL systems to harmonize traffic flows, particularly, in new VSL installations.

### 5.3.1 Methods for Evaluation

Shock waves, which may lead to congestion and crashes, are caused by severe inhomogeneities of the traffic stream that exist when the traffic flow approaches capacity [158]. Smulders [158] named examples of these inhomogeneities as follows:

- speed differences between consecutive vehicles in one lane,
- speed differences that exist across lanes, and
- flow differences across lanes.

Measuring any of the above mentioned inhomogeneities will give indication of a smoothed traffic or otherwise. Harmonization methods aim to eliminate or reduce these inhomogeneities in the traffic stream by applying speed limits to suppress shock waves. However, applying harmonization strategies may not be useful under all traffic conditions. Kerner & Rehborn [74, 159–161] observed three states of traffic flow breakdown from one traffic phase to the other, namely stable, metastable, and unstable traffic states. In the stable traffic state, any disturbance can be resolved without the need of an intervention. In unstable traffic, small disturbances usually result in the inducement of shock waves. According to [74], when the number of vehicles on a road is high and the speed of the traffic stream is also significant (i.e., the metastable traffic state), small disturbances usually will be resolved while large disturbances will lead to shock waves. Thus, if speed limits are intended to dissolve shock waves, the traffic flow must be in the metastable state, because in the stable state there is not much to control and in the unstable state drivers are already unable to move at their desired speed [162].

Algorithms for deploying harmonization strategies of VSL systems may implement reactive and/or proactive strategies. Harmonization of traffic speeds can be activated if congestion is detected. There are times of the day when VSL may be activated in anticipation of congestion. Successively lower speeds (over some distance) may be displayed to gradually reduce speeds over multiple upstream gantries as drivers need time to react before they reach a bottleneck. That is, the ability of the system to convey a coherent picture of the overall traffic situation and prepare drivers progressively for downstream bottlenecks is very important and could influence the ability of the system to reduce inhomogeneities. Therefore, consistency could be used as a measure to assess harmonization. Proper coordination of speeds, along a link, should dampen sudden speed drops and frequent acceleration and deceleration and thereby smooth traffic.

From the foregoing, two methods for assessing harmonization based on the ability of the system to reduce inhomogeneity (speed differential) and the systematic changes of the displayed speed limits (consistency) are discussed.

### 5.3.2 Assessing Inhomogeneity in the Traffic Stream

The steps in evaluating the ability of VSL systems in minimizing speed variance are itemized below:

≫ Reconstruction of GT speeds and flows,
≫ Identification of traffic states, and
≫ Assessing speed variance in metastable traffic state

#### Reconstruction of GT flows

Because traffic variables, including flows, are available only at specific locations and for specific times (point detector data), an estimation of these parameters for all locations along the freeway (ground truth) during the considered time period is required. Method used for the reconstruction of GT speed has been explained previously (see section 5.1.1). GT traffic flows also need to be reconstructed. This is required for the traffic states identification. The adaptive smoothing method is again applied to reconstruct the GT for flow. When estimating the GT for flow, in addition to the flow data gathered by the inductive loops, the ASM function requires speed data as an input. This ensures that the characteristic propagation of traffic information, observed in the different traffic states, is considered.

Figure 5.14 shows an example of the reconstructed flow field for the GT speed situation in Figure 5.2 for the whole day. It can be deduced from the figure that morning and evening peak periods ranged from 7:00-10:00 and 16:00-19:00 hours, respectively. Congested regions (smoothed in upstream direction) are evidently associated with small traffic volumes. The maximum recorded flow for this day was approximately 2700 passenger car units per hour per lane.

#### Identification of Traffic State

Imposing speed limits in stable (i.e., free flowing) traffic may cause unnecessary delay to motorists. Again, VSL information in unstable traffic (i.e., congested

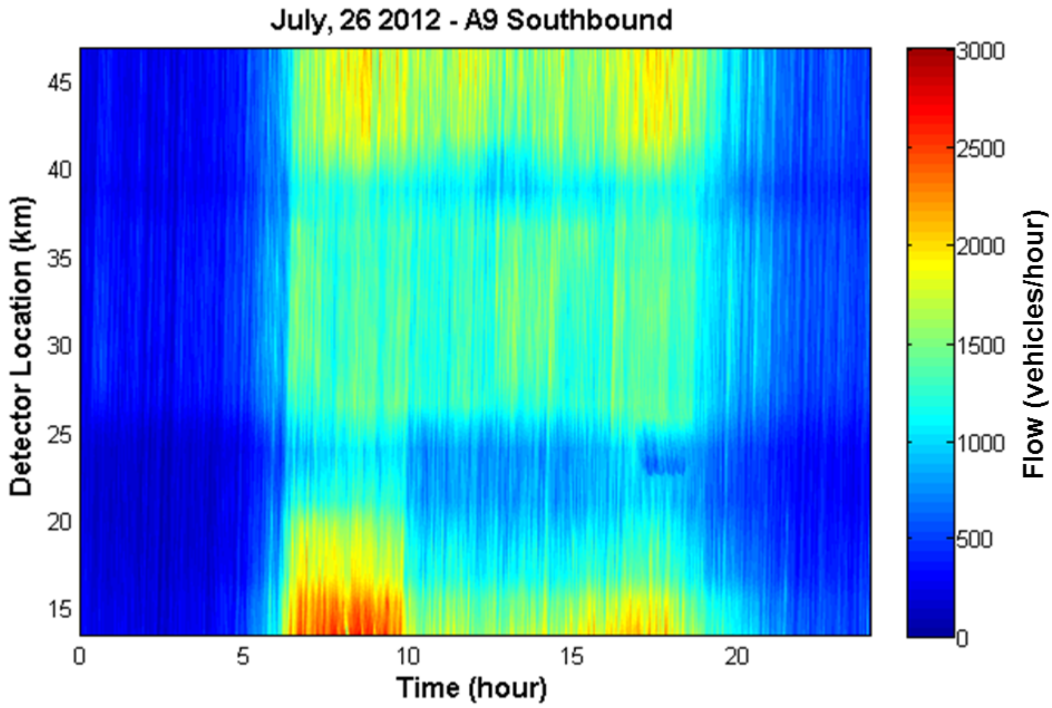



Figure 5.14: Reconstruction of ground truth flow

situations) is of little importance as drivers are, already, unable to travel at their desired speed. For these reasons, application of VSL to harmonize traffic is deemed beneficial only in the metastable traffic state, that is, flows greater than free flow but with speeds greater than congestion speed. This condition occurs when traffic flow exceeds free flow ($q_{min}$) but the speeds are still higher than the critical speed ($V_{crit}$) for traffic to transit into congestion state. Recommended values for $q_{min}$ and $V_{crit}$, above which harmonization benefit could be expected, are 600 vehicles/h/lane and 60 km/h, respectively [48, 69, 163]. A sensitivity analysis on the traffic flow could also be done to select the optimal values for these thresholds.

By superimposing the GT speeds and flows, the different traffic states are identified. The steps for the traffic state assignment are illustrated in Figure 5.15. The algorithm, first of all, compares the reconstructed spatio-temporal traffic flow ($q$) matrix to $q_{min}$. Regions with flows below $q_{min}$ constitute stable traffic state. Next, the reconstructed spatio-temporal speed ($u$) is brought into the estimation and matched with $q$. Spatio-temporal regions with traffic flow exceeding $q_{min}$ and speeds greater than $V_{crit}$ constitute the metastable traffic state. Regions with speeds less than $V_{crit}$ represent unstable traffic state. The green, yellow, and red regions in Figure 5.16 represents stable, metastable, and unstable traffic states for the traffic situation shown in Figure 5.2 and Figure 5.14 on the autobahn

A99, near Munich, Germany. Apparently, on this particular day, traffic should be harmonized only during the daytime. This is consistent with the times the VSL at the study location is activated as indicated in subsection 4.1.1.

```
Initialization:  q = traffic flow;
                 u = speed;
                 V_crit = congestion speed;
                 q_min = free flow volume
                 traffic_state = traffic state

Step 1       if q ≤ q_min
                 traffic_state = stable
Step 2       else if  q > q_min & …
                 u > V_crit
                 traffic_state = metastable
Step 3       else if u ≤ V_crit
                 traffic_state = unstable
             end if
```

Figure 5.15: Algorithm for traffic states identification

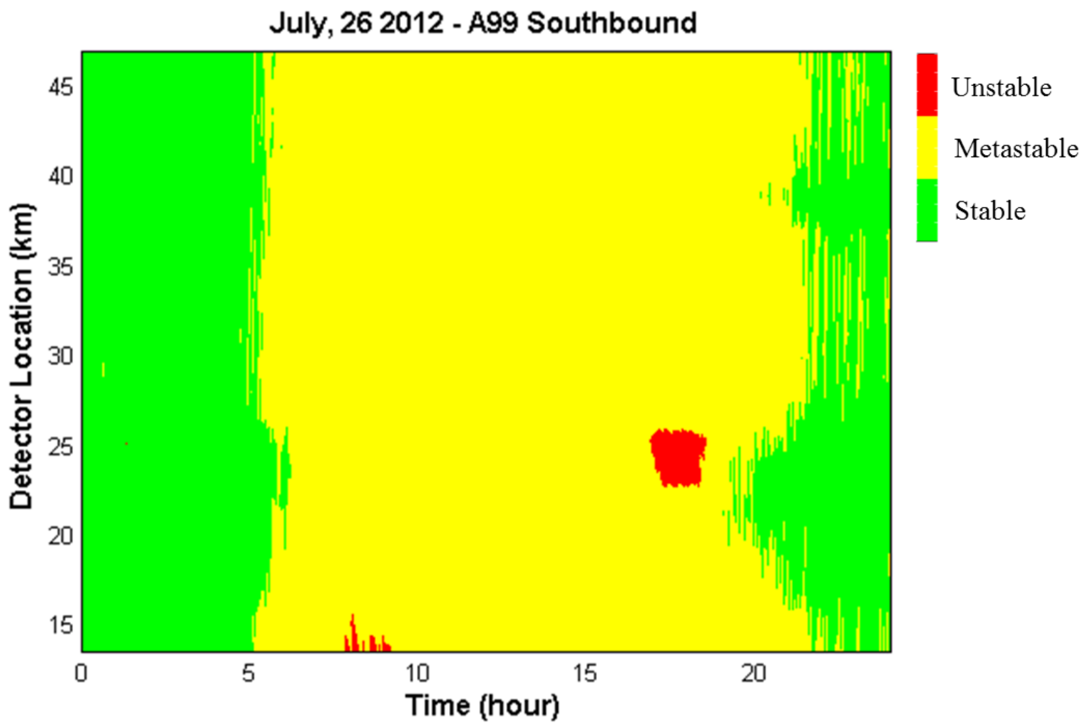



Figure 5.16: Spatio-temporal representation of the different traffic states

#### Quantifying Speed Differentials

Once the traffic state has been determined, the ability of the system to reduce inhomogeneities in the metastable traffic state is evaluated. The standard deviation (SD) of speeds, which is also collected by the dual inductive loop detectors, is used for this purpose. The SD measures the spread of the speed data from the mean. However, knowing the standard deviation alone gives little information about the relative variability since it is based on the sampled data and as such, must be understood in the context of the mean about which it occurs. To make it meaningful to compare data sets gathered from different detector stations, the coefficient of variation (CV) is used. The CV is the ratio of the standard deviation to the mean, that is,

$$CV = \frac{Standard \quad Deviation}{Mean} \tag{5.15}$$

The CV is a standardized measure of dispersion and helps to determine the relative magnitude of variability in the traffic stream. A small CV indicates low speed differential and thus is used as indicator for smoothed traffic.

### 5.3.3 Evaluating Consistency

The steps in evaluating the ability of VSL systems to systematically vary the displayed speed limits are as follows:

- ≫ Generation of trajectories based on GT,
  - ≫ Space-time representation of VSL,
    - ≫ Determine time at which a gantry is passed,
      - ≫ Use time to identify the displayed speed limit,
        - ≫ Scenario assignment, and
          - ≫ Aggregate different scenario types.

The GT speed has been reconstructed (section 5.1.1) and trajectories generated (subsection 5.2.1). Next, the VSL matrix is produced.

### Representation of VSL Matrix

Information on the variable speed limits displayed by the system is also logged and available for the study. A spatial-temporal matrix, containing all speeds displayed to drivers, can therefore be produced. Spatially, the VSL is controlled by the positions of the gantries just as in the case of the messages (subsection 5.1.3). Since the system is dynamic, the time range for which a speed limit is displayed determines the temporal extent. Figure 5.17 shows a graphical representation of an example VSL signs matrix. It is worthy to note that, in congested traffic situations ($speeds < 60km/h$) and in free flowing conditions ($speeds > 120km/h$), the VSL system does not display any speed information and these regions are designated by "no sign" in Figure 5.17.

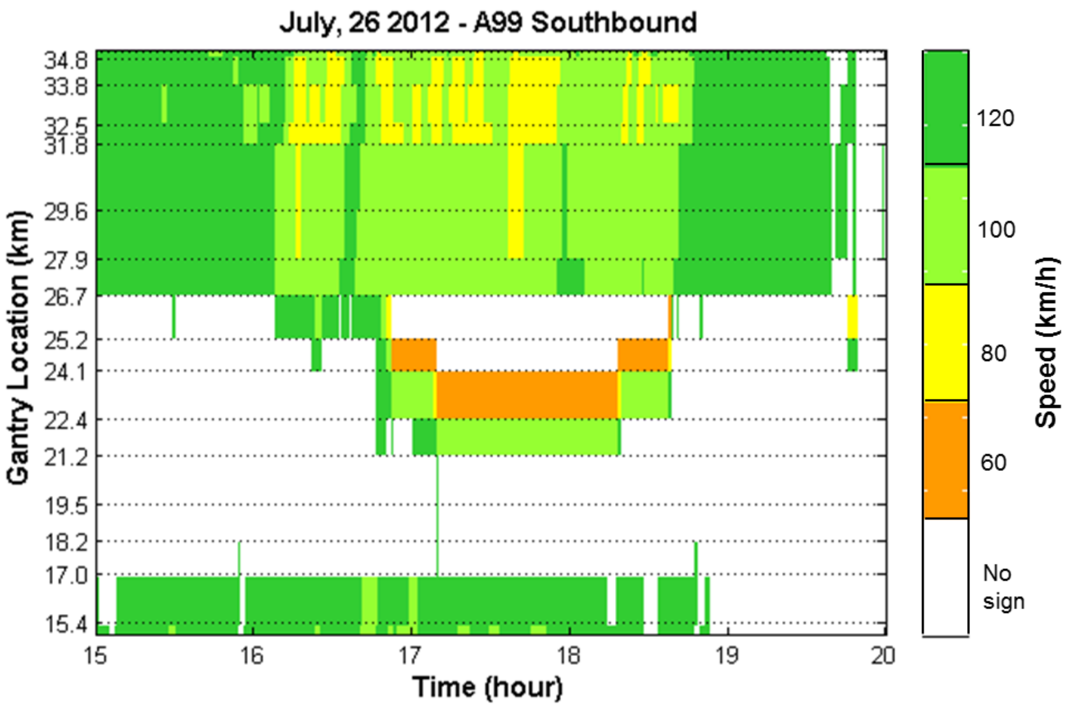



Figure 5.17: VSL plot with no information for congested and free flowing traffic

### Speeds in Congested and Free Flowing Conditions

Because no speed information is displayed in both congested and free flowing conditions, an approach to distinguish between them became necessary. In addition to the speed limit information, the system at the study location also displays warning messages. A spatio-temporal matrix of the messages displayed to drivers has already been discussed in subsection 5.1.3. In congested traffic conditions, the sign “congestion” is displayed (see Figure 5.5 for an example contour plot of variable message signs). The VSL matrix and the message sign matrix are then superimposed. Typical values to represent congestion and free flowing speeds need to be defined. Congested traffic is represented with a speed of 30 km/h whilst free flowing traffic is represented with a speed of 130 km/h in this study. All “no sign” regions on the VSL plot that were indicated by “congestion” on the message sign plot were replaced with a speed of 30 km/h. All other “no sign” regions were replaced with a speed of 130 km/h to obtain the complete component of the VSL matrix as shown in Figure 5.18.

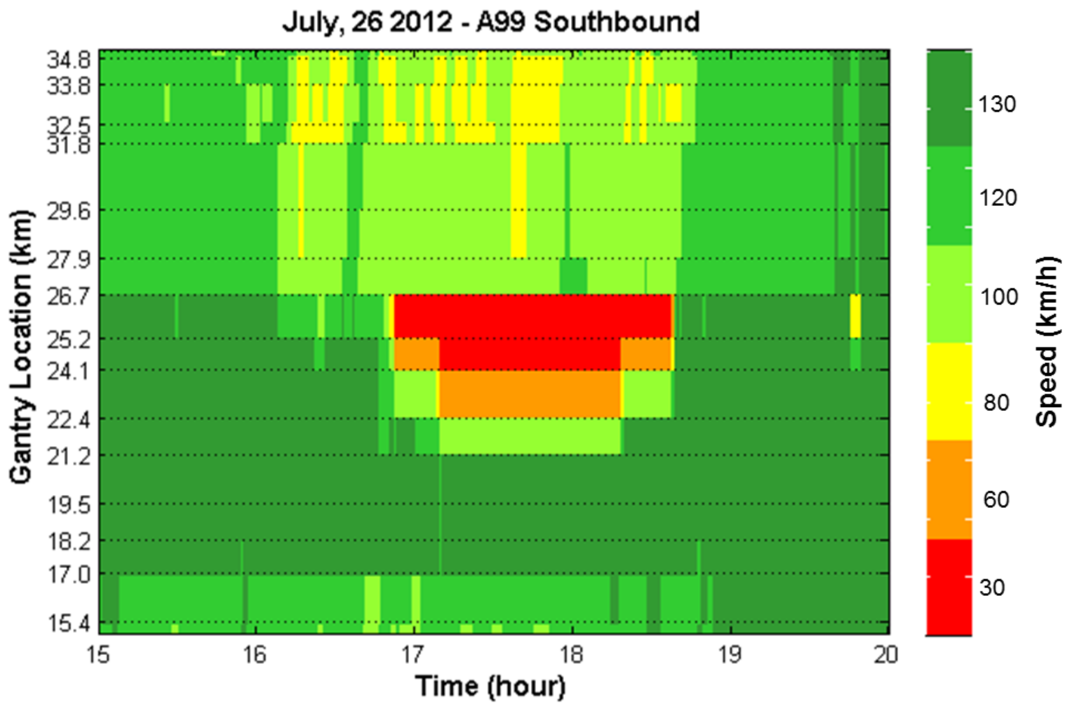



Figure 5.18: Complete VSL contour plot

### Sequence in Displayed Speeds

Virtual trajectories, generated from the reconstructed GT, make it possible to determine the speed limits drivers encounter as they traverse the route. The method is the same as used to obtain dynamic messages received by drivers. Many trajectories are generated to cover the whole road segment throughout the considered time period. Considering the generated trajectories independently, the times at which a virtual vehicle passes a particular gantry are noticed. The observed times are then used to obtain the speed limits displayed by the system at the time a gantry is passed. Figure 5.19 illustrates the superimposition of all generated trajectories on the displayed speed limits between 15:00 and 20:00 hours. In doing so, the sequence in speed limits experienced by vehicles on trajectories are obtained and analyzed.

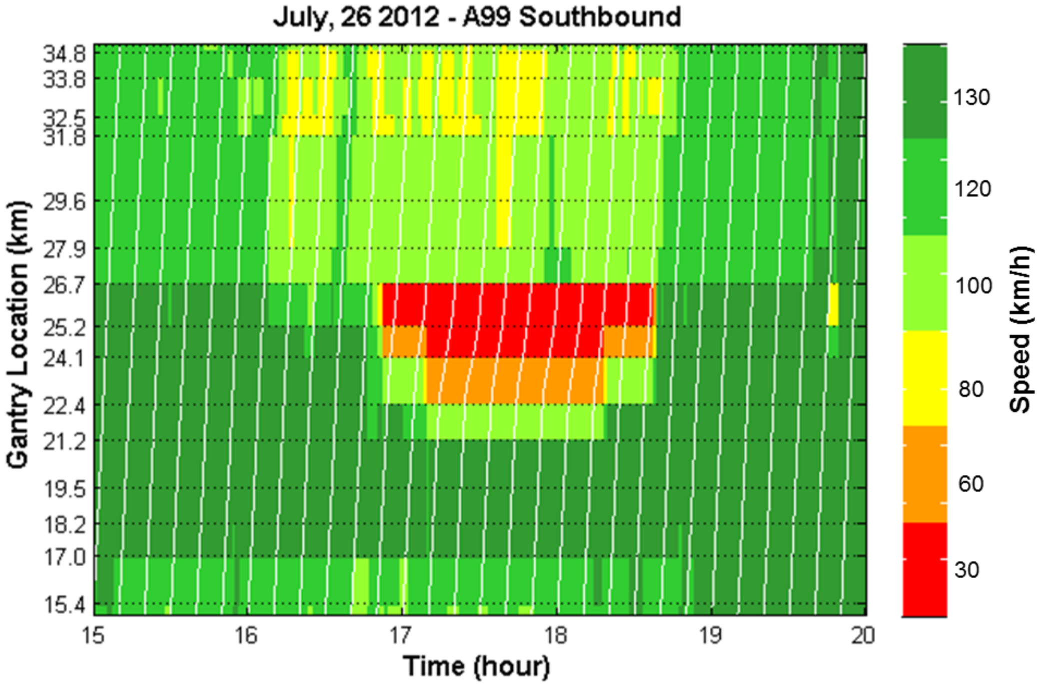



Figure 5.19: Determination of speed limits encountered by drivers

### Possible Scenarios Encountered by Drivers

The scenarios described below have been identified as possible sequences of speed limit signs which vehicles using the freeway with a VSL facility installed on it can experience. Examples for each of the scenarios, based on simulated trajectories on the autobahn A99 near Munich, Germany, are illustrated in Figure 5.20. The assessment of the consistency of the system is based on these scenarios.

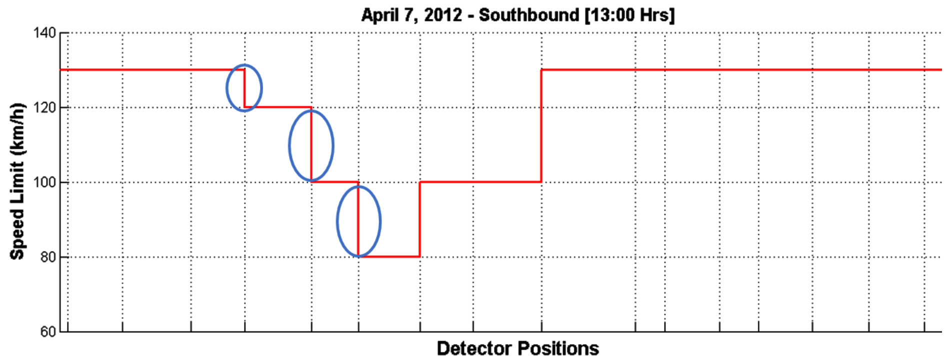
*Scenario T.1 - Gradual Speed Drop*: Gradual speed reduction is a very important component of VSL systems. Systematically reducing traffic speeds ensures a smooth transition from high speeds to lower speeds. This ultimately prevents surprises that are likely to be encountered by a driver. The variable message signs at the study location display speed limits in multiples of 20 km/h. A one step decrement from one gantry to the next is considered appropriate and ensures a gradual transition from one speed class to the other.

*Scenario T.2 - High Speed Drop*: Problems in adapting to a newly displayed speed limit will arise if the decrement is drastic. Specifically, changing a speed limit by more than one step (e.g., from 120 km/h to 80 km/h) may cause speed adaptation issues and rapid decelerations. Therefore, if the displayed speed limit was to be reduced from say 120 km/h to 80 km/h, then there should be a middle gantry to display 100 km/h to provide a gradual transition for drivers. A high speed drop, defined as a drop of more than one step, is considered inappropriate.

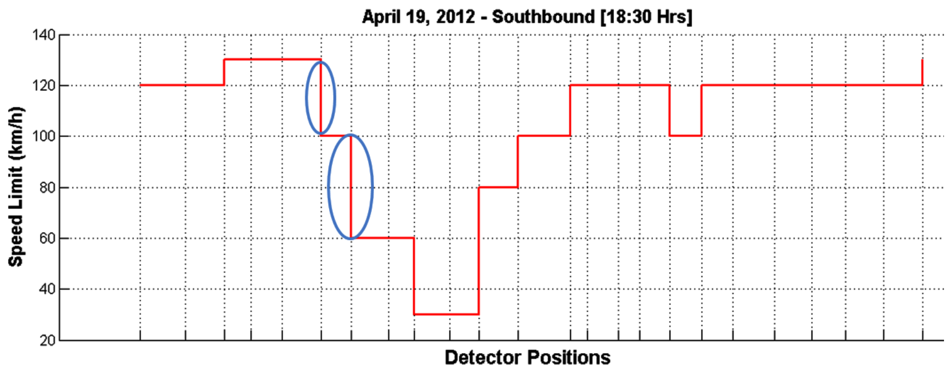
*Scenario T.3 – Constant Speed at Consecutive Gantries*: The speed limit displayed at the immediately passed upstream gantry may be maintained at the next downstream gantry if the traffic environment remains unchanged. This may also be to control traffic speeds in anticipation of a traffic breakdown. Maintaining a constant speed at successive gantries does not bring any adverse effect on stability and is considered as appropriate.

*Scenario T.4 - Speed Increase*: A speed increase is not expected to follow the same pattern at which it was decreased. While a gradual speed decrease upstream of a bottleneck may be applied to ensure a gradual reduction of vehicle speeds, increasing speeds downstream of a bottleneck may be used to urge drivers to accelerate in order to increase the discharge rate at a bottleneck. Therefore, a speed increase (whether gradual or rapid) is not considered as undesirable for the system.

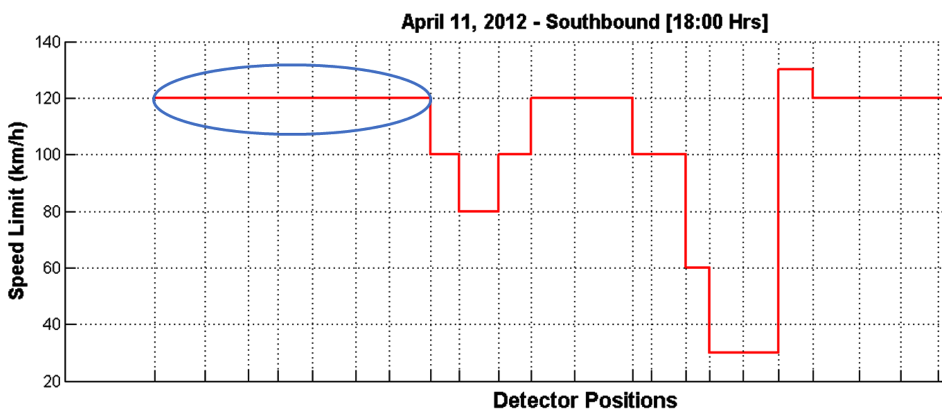
*Scenario T.5 - Roller Coaster Pattern*: The traffic state experienced on a road segment can change over a short time interval as in stop-and-go traffic. Stability in a VSL system is necessary to prevent speed limits from being displayed for very short durations. Requiring drivers to accelerate, and then to decelerate over a short period does not bring any benefit to the system. However, this situation is considered differently from where drivers are required to slow down even for a short time because of an incident in a section of the road. The latter, may have consequences on safety. A "roller coaster" pattern is therefore defined as when speed increases last for short times or distances (i.e., if the distance between the last speed increase and first speed decrease is less than 3500 m). Drivers require time to react to incidents and speed limits displayed ahead of them. On the contrary, posting messages too far upstream of an incident is also not beneficial as drivers might tend to forget about the warning [157]. The distance of 3500 m is chosen according to engineering judgment and the highest recommended distance within which drivers are able to recall a displayed advance warning on a freeway [157]. The roller coaster pattern is considered detrimental to the system.



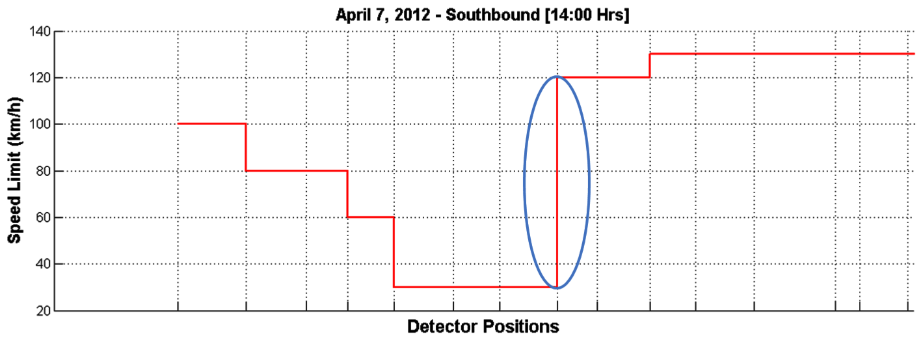

(a) Gradual speed drop



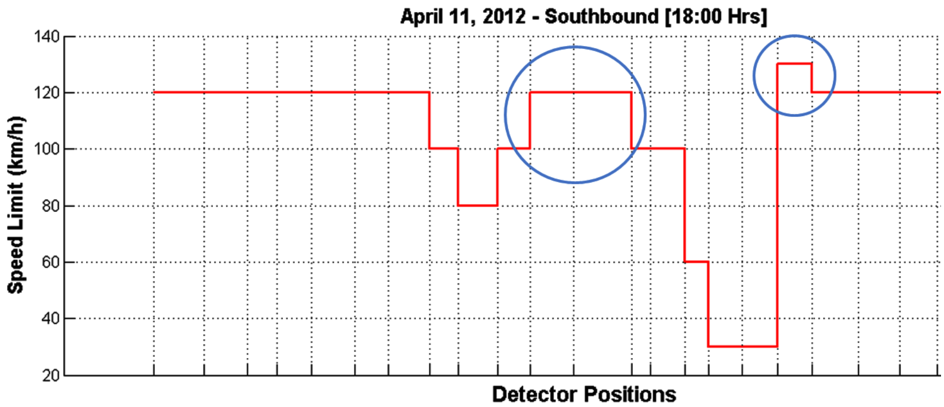

(b) High speed drop




(c) Constant speed at consecutive gantries




(d) Speed increment




(e) Roller coaster pattern

Figure 5.20: Scenarios of consecutive variation in displayed speed limit signs

### Aggregating Consistency

The idea of the consistency assessment is to observe changes in the displayed speed limits as one travels along the freeway corridor. As a vehicle trajectory is followed, a check is made as to which of the scenarios described above were encountered along the route. The algorithm firstly assigns the consecutive variations in the speed limits of a considered trajectory to one of scenario types T.1 – T.4 as in Figure 5.21. This is done by calculating the arithmetic difference in the speed limits displayed by the currently considered gantry ($VSL_i$) and the next downstream gantry ($VSL_{i+1}$). Using the VSL system at the study location as an example, if the difference in the speeds displayed by the two gantries is 20 km/h (i.e., gradual speed drop), the algorithm assigns the encountered situation to scenario type T.1. In the case that the difference in the speed limits is more than 20 km/h, it is designated as T.2 and as T.3 if there is no speed change. Whenever the speed difference is less than zero, the scenario type is assigned to T.4. The procedure is repeated for the next until it gets to the last but one gantry. For the last gantry, no determination could be made as there is no speed limit downstream.

```
Initialization:  i = 1;
                 sc_type = scenario type;
                 VSL(end-1) = last but one VSL;

Step 1      for (i ≤ VSL(end-1)) Do ...
Step 2           if VSL(i) - VSL(i+1) == 20;  sc_type(i) = T.1
Step 3           else if VSL(i) - VSL(i+1) > 20;  sc_type(i) = T.2
Step 4           else if VSL(i) - VSL(i+1) == 0;  sc_type(i) = T.3
Step 5           else if VSL(i) - VSL(i+1) < 0; sc_type(i) = T.4;
Step 6           i = i + 1
Step 7           end if
Step 8      end for
```

Figure 5.21: Assignment of variation in speeds to scenario types T.1-T.4

When the sequence in speed limits allows drivers to accelerate and decelerate over a short distance, they constitute roller coaster pattern (scenario T.5). After the initial assignments (T.1-T.4), the algorithm looks for gantries in which there are speed increases (T.4) and then either a gradual (T.1) or sharp (T.2) speed drop to determine if they constitute roller coaster pattern. Accordingly, all identified scenario types from the earlier assignments are required as input. In the next stage, the distance between the two gantries where the rise and fall in the speed limits occurred are calculated. The VSL gantry positions (chainages or kilometer posts) are therefore also needed. If the distance between the gantries is 3500 m or less, the situation is designated roller coaster pattern (T.5). It is noteworthy that scenario type T.3 (i.e., constant speed at consecutive gantries) can be in-between the gantries in which the speed increase and then the decrease were located. The algorithm for the assignment of scenario type T.5 is shown in Figure 5.22.

```
Initialization:  i = 1;
                 sc_type(end) = Last scenario type;
                 VSL_pos = VSL gantry position

Step 1      for (i ≤ sc_type(end)) Do ...
Step 2          if sc_type(i) == T.4
Step 3              j = i + 1
Step 4              for (j ≤ sc_type(end)) Do ...
Step 5                  if sc_type(j) == T.4
Step 6                  break (exit the loop)
Step 7                  else if sc_type(j) == T.1 or T.2 & ...
Step 8                      VSL_pos(j) - VSL_pos(i) ≤ 3500 ...
Step 9                      sc_type(i) = T.5;
Step 10                     break (exit the loop)
Step 11                 end if
Step 12                 j=j+1
Step 13             end for
Step 14             i = i + 1
Step 15         end if
Step 16     end for
```

Figure 5.22: Assignment of scenario type T.5

Considering all generated trajectories, a set of all experienced scenarios $S_1, S_2, S_3, \ldots, S_N$ is obtained. This set is categorized and used to check the overall consistency of the VSL system. The assessment is done based on successful consistency rate ($SCR$) and failed consistency rate ($FCR$). All desirable scenarios types (T.1, T.3, and T.4) are assigned to the set successful consistency ($SC$), and all unsuitable scenarios types (T.2 and T.5) are assigned to the set failed consistency ($FC$). That is, the sizes of $SC$ and $FC$ are calculated by Equation 5.16 and Equation 5.17, respectively.

$$SC = \sum Id_{\{T.1,T.3,T.4\}}(S_j) \tag{5.16}$$

$$FC = \sum Id_{\{T.2,T.5\}}(S_j) \tag{5.17}$$

where

$$Id_A(b) = \begin{cases} 1, & if \;\; b \in A \\ 0, & else \end{cases}$$

The $SCR$ and $FCR$ are estimated by calculating the percentages (%) of $SC$ and $FC$ scenarios over all scenarios, respectively. Note that at times when free flowing traffic conditions prevail along the entire freeway corridor, the VSL is not active (no speed information is displayed). Applying the method described above under this condition will always assign scenario type T.3 which belongs to the set $SC$ for all observations although in reality, traffic was not harmonized. Therefore, virtual vehicles that did not encounter any displayed variable speed limit along their entire trajectories are excluded from the analysis. This ensures that the method focuses on assessing the system's consistency only during relevant periods.

# Chapter 6

# Comparative Study of VSL and RTTI

Methods for assessing the different characteristics of VSL systems have been presented in chapter 5. In the following, a different quantitative method, which can also be used to evaluate ATIS is introduced. Before the quantitative comparative study to establish inconsistency, if any, in the traffic information provided by VSL and RTTI systems is performed, descriptive analysis is carried out on the two traffic information data sources to understand their characteristics.

## 6.1 Common Approaches to Qualitative and Quantitative Analysis

The initial methods for both the qualitative and quantitative VSL and RTTI comparisons are the same, and not much different from what has been previously described. However, it is carried out on two different data sources. The procedure is again itemized below:

≫ Reconstruction of GT speeds from loop detector data,

≫ Discretization of GT according to VSL and RTTI grids,

≫ Space-time representation of VSL system and RTTI speeds.

### 6.1.1 Ground Truth for VSL and RTTI

Ground truth traffic speed is reconstructed from point detector data using the ASM. This GT is use to represent actual traffic for the two data sources. Figure 6.1 shows an example GT space-time speed map for June, 27 2012. Any traffic information broadcast on this day must reflect what is shown in the figure.

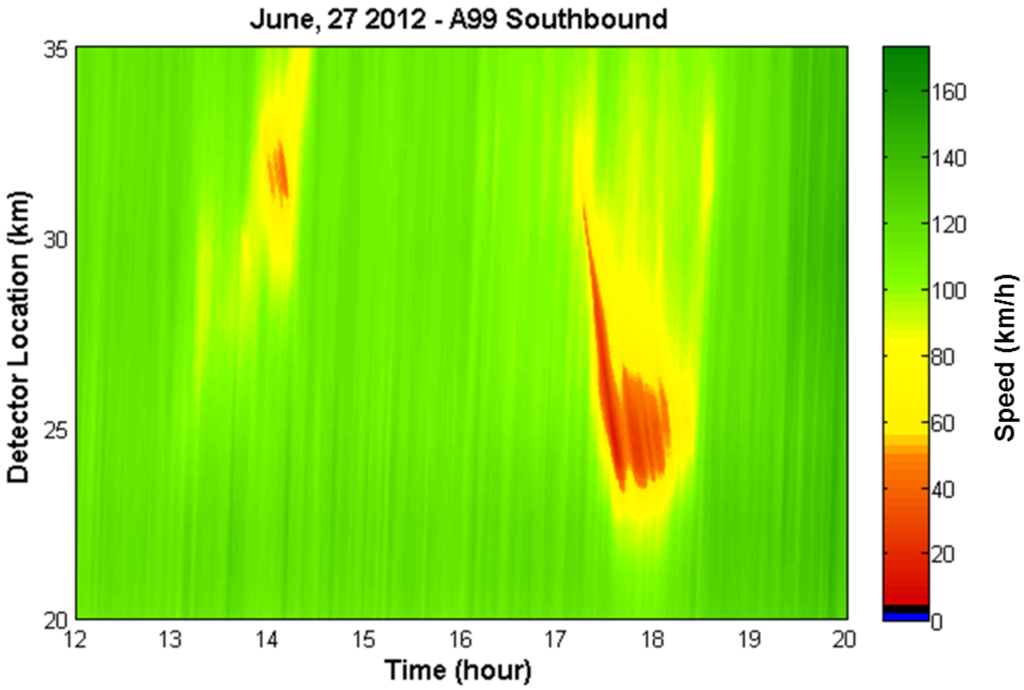



Figure 6.1: Reconstruction of GT using ASM

### 6.1.2 Discretization of GT - VSL and RTTI

The speed limit displayed on the overhead gantries of VSL systems are effective until the next downstream gantry is reached. Broadcast RTTI also represents the information for the considered TMC segment. As mentioned, using the continuous GT to assess the “discrete” VSL/RTTI information may not be fair. In order to make a good match between the GT and the displayed speeds, the GT is discretized to assume the same grid as the positions of the gantries or TMC locations. Using the new positions as borders, the continuous ASM matrix is discretized and each grid is represented with the minimum speed value within the segment. By discretizing the GT to the grids of the gantries or TMC locations, comparisons between reality and broadcast information can be performed. Figure 6.2 and

Figure 6.3 show an example of a Min-TGT contour plot for VSL and RTTI, respectively for the GT situation in Figure 6.1.

Looking at the two figures, it is observed that the VSL borders (gantry positions indicated by dotted horizontal lines in Figure 6.2) are entirely different from the RTTI borders (TMC locations indicated by dotted horizontal lines in Figure 6.3). The VSL gantries are densely spaced in relation to the TMC locations of RTTI. Overall, matching the Min-TGT of the two information sources to reality, the Min-TGT for VSL approximates better to the GT than the Min-TGT of RTTI. The better approximation of the VSL's Min-TGT to the GT may be due to the relatively shorter distances between the gantry locations as compared to the TMC segments of RTTI. Representing shorter segments with a single speed value will definitely be more accurate than long distances.

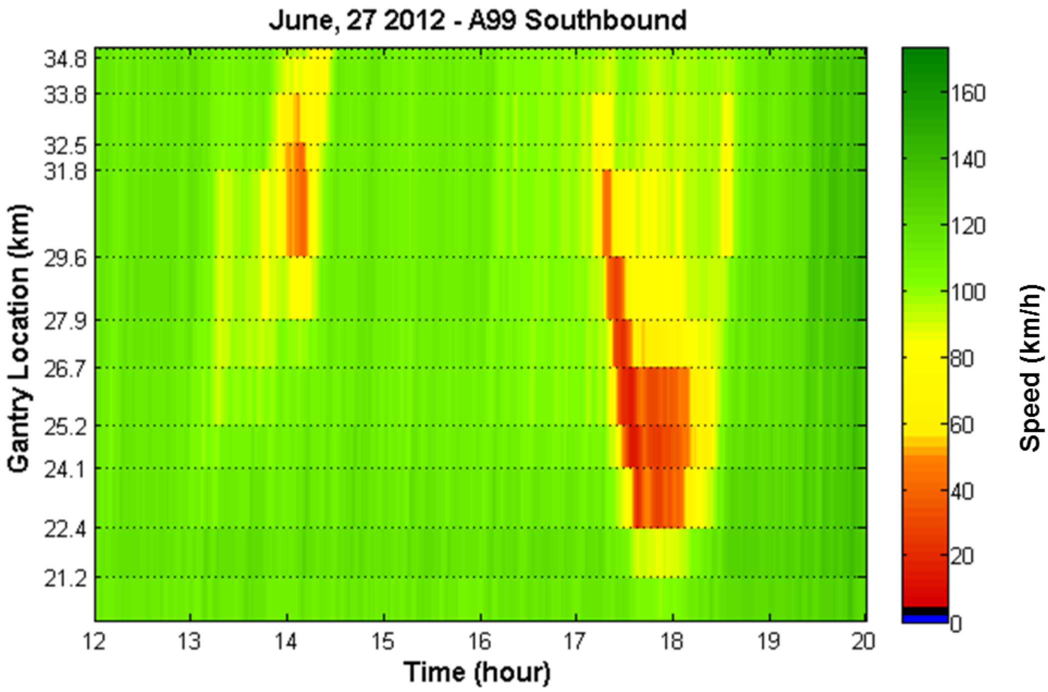



Figure 6.2: Discretization of GT (Min-TGT) – VSL

### 6.1.3 Space-time Representation of VSL and RTTI

The speeds displayed by the VSL and RTTI are represented in space-time as in Figure 6.4 and Figure 6.5, respectively. Notice again that the VSL at the study location does not display any speed in congestion and free flowing conditions. For RTTI, speed information is displayed in all traffic conditions and at all

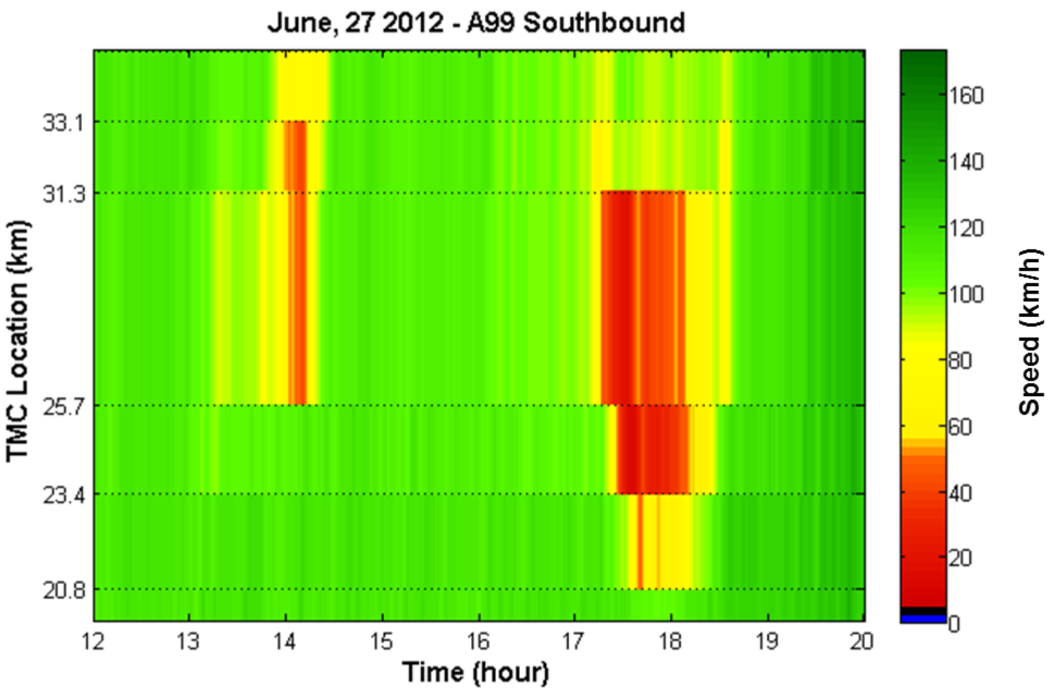



Figure 6.3: Discretization of GT (Min-TGT) - RTTI

times. Differences between the broadcast information and the discretized GT are determined in the subsequent sections. However, an observation between the Min-TGT for RTTI and broadcast RTTI must be mentioned. The provider, mostly, tends to broadcast somewhat higher speeds in congestion. In a whole, similarities in pattern in the space-time speed maps can be observed when the VSL and RTTI information broadcast is matched with their corresponding discretized GT.

## 6.2 Qualitative Comparative Analysis of VSL and RTTI

The method employed here was used by Riggins, et al. [164] to evaluate the compliance level of VSL systems. It is extended in this study to include RTTI. When the GT is discretized to assume the grids of the VSL/RTTI, the size of the new GT matrix becomes the same as the size of the traffic information matrix so that they can be matched in space and time.

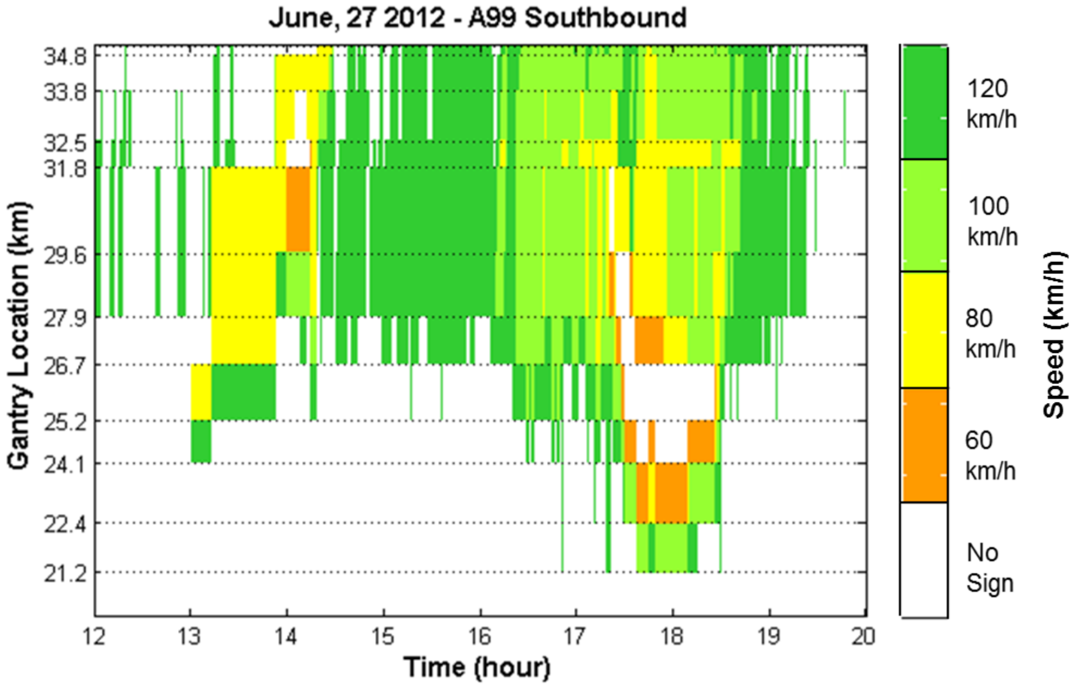



Figure 6.4: Space-time representation of VSL

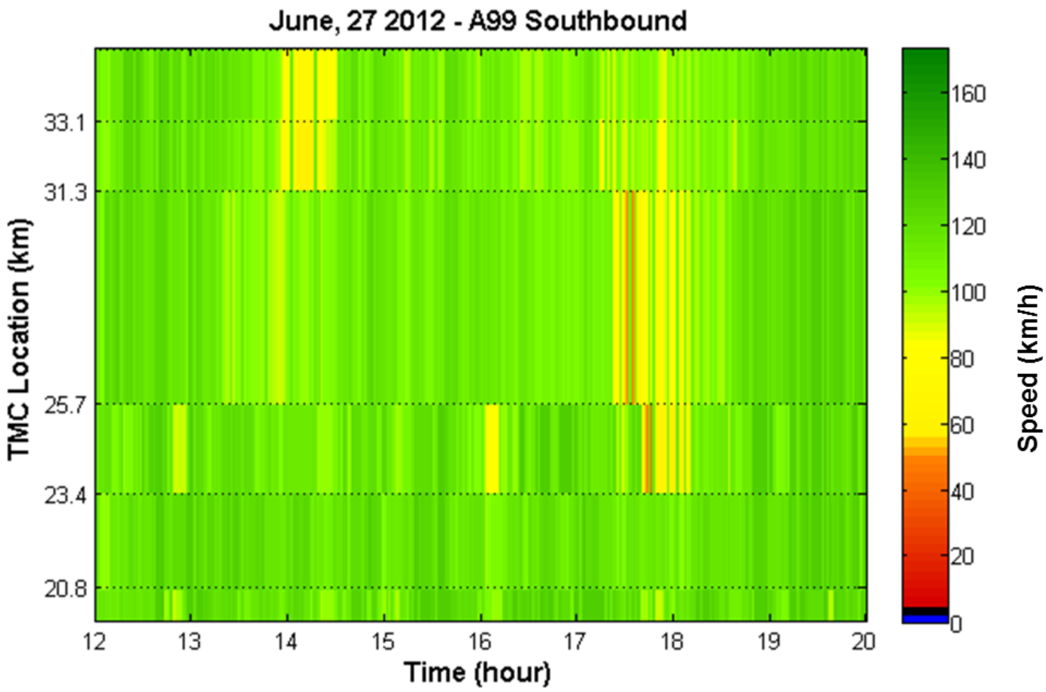



Figure 6.5: Space-time representation of RTTI

### 6.2.1 Difference Matrix

In studying whether there are differences in the information provided by the two sources, firstly, a difference matrix is obtained. This is done by subtracting the respective traffic information matrices (i.e., VSL and RTTI) from their discretized GT matrices. The difference matrix gives an idea of how close or otherwise the broadcast information is from reality. Figure 6.6 and Figure 6.7 show the contour plot for the difference matrix of VSL and RTTI, respectively. In the case of the VSL system, no determination is made at times when the system does not display any speed information. Largely, from the two figures, the differences between the Min-TGT and the traffic information were within ±20 km/h.

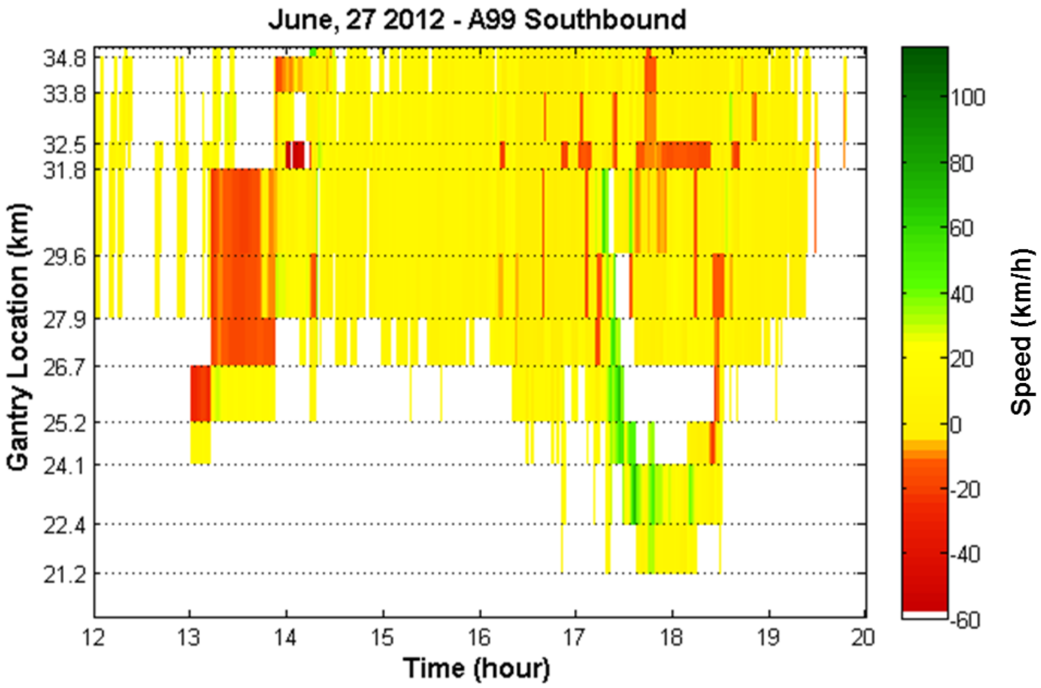



Figure 6.6: Difference between Min-TGT and VSL

### 6.2.2 Difference Histogram

Using the difference matrix which now contains information on the deviation of the traffic information from the Min-TGT, a histogram is created. From the histogram, the distribution of the broadcast information around the GT can be observed. Figure 6.8 shows the histogram for VSL and Figure 6.9 that for RTTI for their respective difference matrices for June, 27 2012. Using the distribution of the deviation of the broadcast speed from the GT, deductions can be made on the performance of the two systems. This will be illustrated in the case study in subsection 7.4.1.

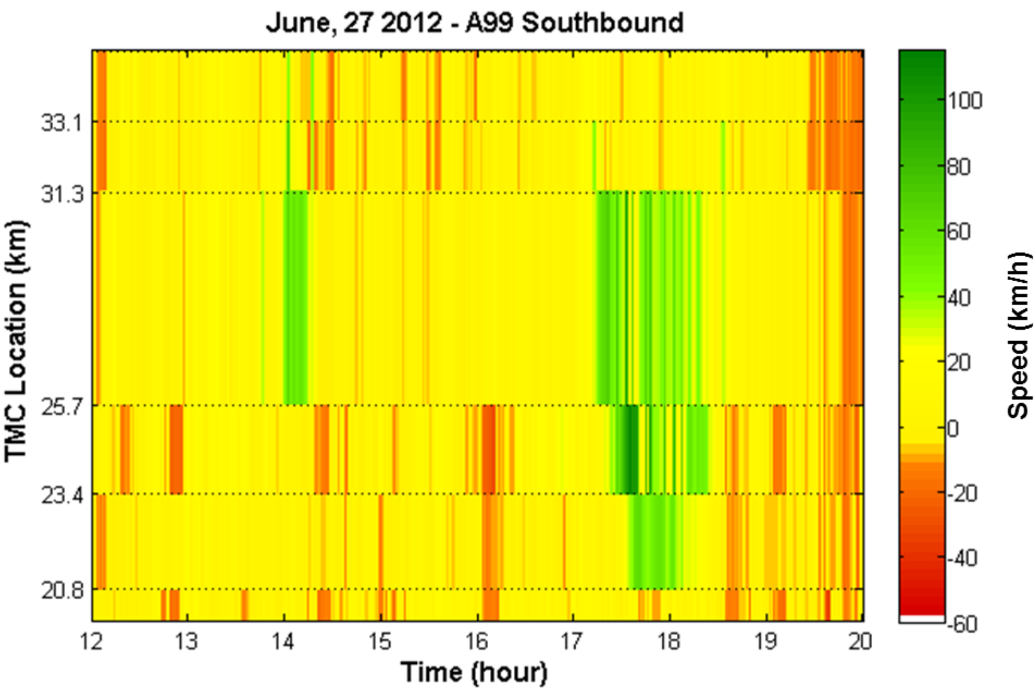



Figure 6.7: Difference between Min-TGT and RTTI

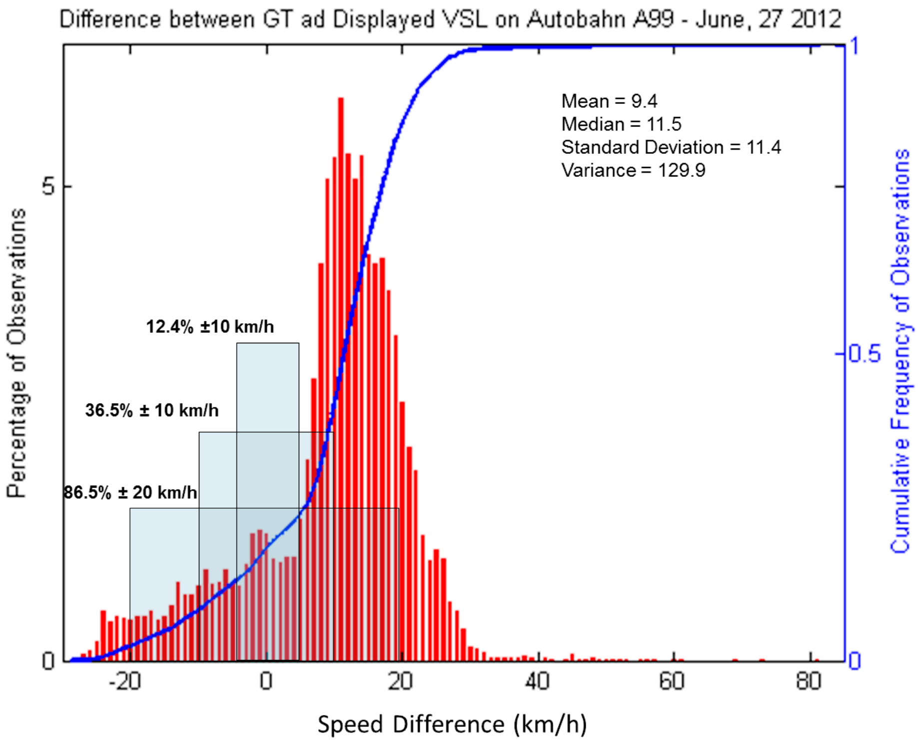



Figure 6.8: Difference histogram for VSL

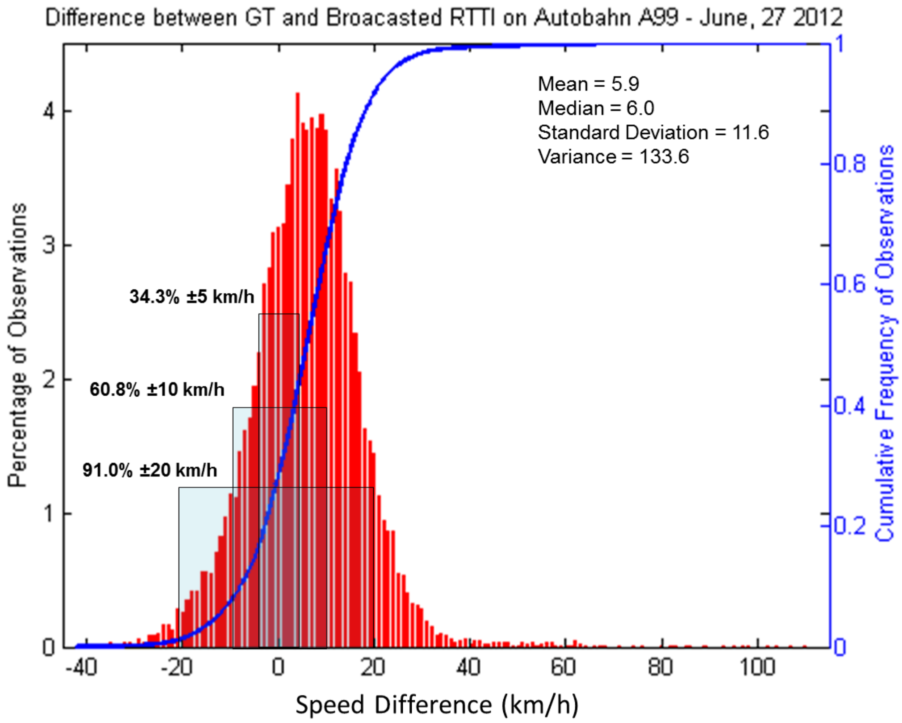



Figure 6.9: Difference histogram for RTTI

## 6.3 Quantitative Comparison of VSL and RTTI

A modified version of the QKZ method for comparing traffic information from different sources is presented. A limitation in the broadcast information has already been taken care of by discretizing the GT to assume the grids of the gantries of the VSL or TMC locations. Another addition to the QKZ method is the inclusion of a predictive buffer upstream of congested regions, or providing traffic information just before the onset of actual congestion. The concept is presented below.

### 6.3.1 Predictive Buffer

Optimal control approaches include the prediction of congestion in their control strategies. Congestion prediction, if done well, will have a positive influence on traffic management as speed control interventions do not have instantaneous effect on traffic [77]. Looking at it from the safety perspective, giving warning in advance of a dangerous situation prepares drivers to take cautionary actions to forestall traffic crashes. As stated earlier, warning messages should also not be placed too far from the traffic situation as drivers may forget or assume false alarm.

Therefore, receiving congestion report before the beginning of actual congestion can be considered as positive (i.e., an advance warning message) if the extent of the "false" message is just right to be considered as an advance warning. In the temporal sense, this can be interpreted as correctly predicting and issuing warning to drivers before the onset of congestion. Indeed, earlier studies (e.g., [146, 149]) have established that significant proportion of missed detections occur at the commencement of congestion and recommended the use of models to predict the start of congestion in active traffic management. Therefore, traffic information providers who are able to do this should not be penalized for doing something which is desirable in the field.

Based on recommendations from [157] and engineering judgment, a congestion warning message up to a distance of 3500 m from the tail of congestion, or in the temporal sense 180 seconds before the beginning of congestion is considered not as a false alarm, but as a predictive buffer. The 180 seconds was chosen with the assumption that drivers are traveling at a speed of 70 km/h. Since the predictive buffer regions are, in reality, not congested, the 70 km/h on a freeway is presumed to be quite considerate toward the provider.

### 6.3.2 QKZ Method with Predictive Buffer

The QKZ method has been described already in this dissertation (section 3.2.2 & subsection 5.1.5). It compares the space-time congestion areas of the GT to the space-time congestion areas of the traffic information. The interpretation of this is that the method presumes the prediction by optimal control approaches, even if it is done accurately, as false alarm. In this dissertation, predictive buffers are treated as detections. Figure 6.10 and Figure 6.11 show actual congestion areas and areas covered by traffic information without and with predictive buffers, respectively. Predictive buffer areas are marked with color yellow.

To be able to accommodate and measure the effect of the predictive buffer, the $QKZ_1$ and $QKZ_2$ equations need to be modified. First, $E$ (i.e., GT congestion) can be extended at the rear to a limit equal to the acceptable distance (spatial buffer) or time (temporal buffer) of giving advance warning or predicting congestion. In the example of Figure 6.11, temporal buffer with a limit of 180 seconds was adopted. If congestion is predicted and broadcast, the additional information area within the buffer region, which otherwise would have been a false alarm, is calculated. Assuming that spatial buffer is considered, the broadcast area

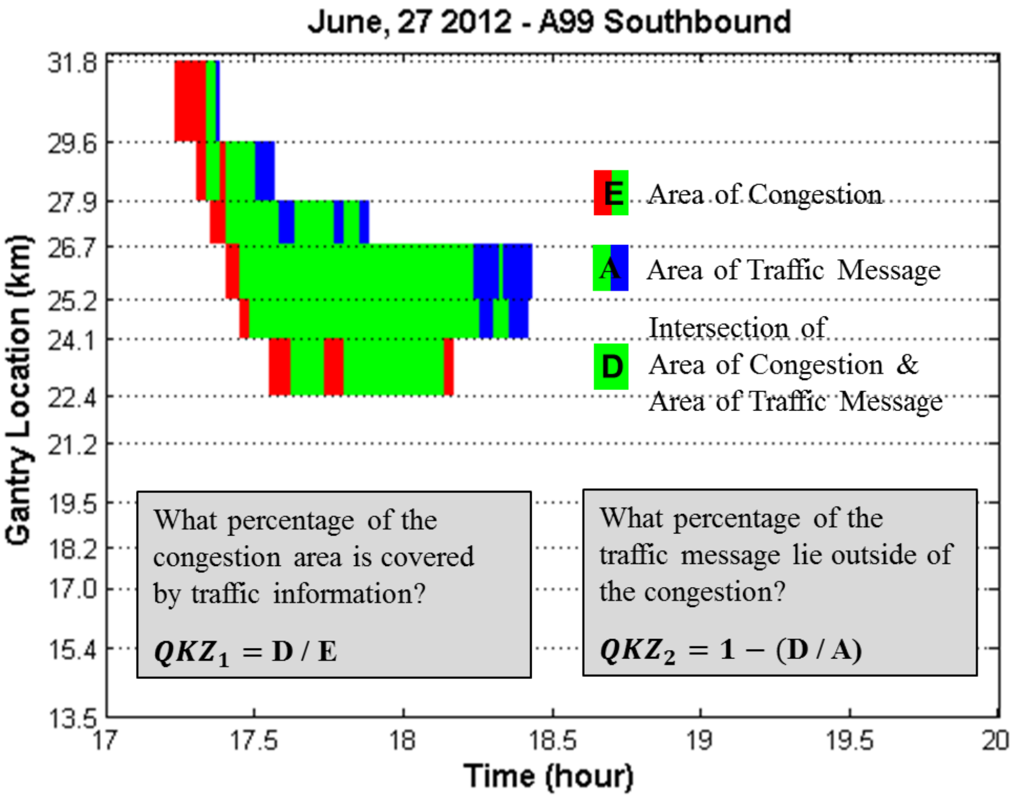



Figure 6.10: Estimation of $QKZ$ indexes without predictive buffer

downstream of GT congestion is computed. That is, in a situation where drivers receive warning before actual congestion. Let's denote the area of the prediction or traffic message before the GT congestion area by $B$. Notice that this situation is different from when the congestion area falls upstream of the information area (no or late traffic warning). The later situation may result in crashes and is wholly taken as a negative situation (missed detection). This means that the GT congestion area $E$ and the intersection area $D$ will also increase by the area of the predictive buffer, $B$. Therefore, the following equations for the new quality indexes, $QKZ_{1N}$ and $QKZ_{2N}$, result:

$$QKZ_{1N} = \frac{D'}{E'} \tag{6.1}$$

$$QKZ_{2N} = 1 - \frac{D'}{A} \tag{6.2}$$

$D'$ and $E'$ are defined by:

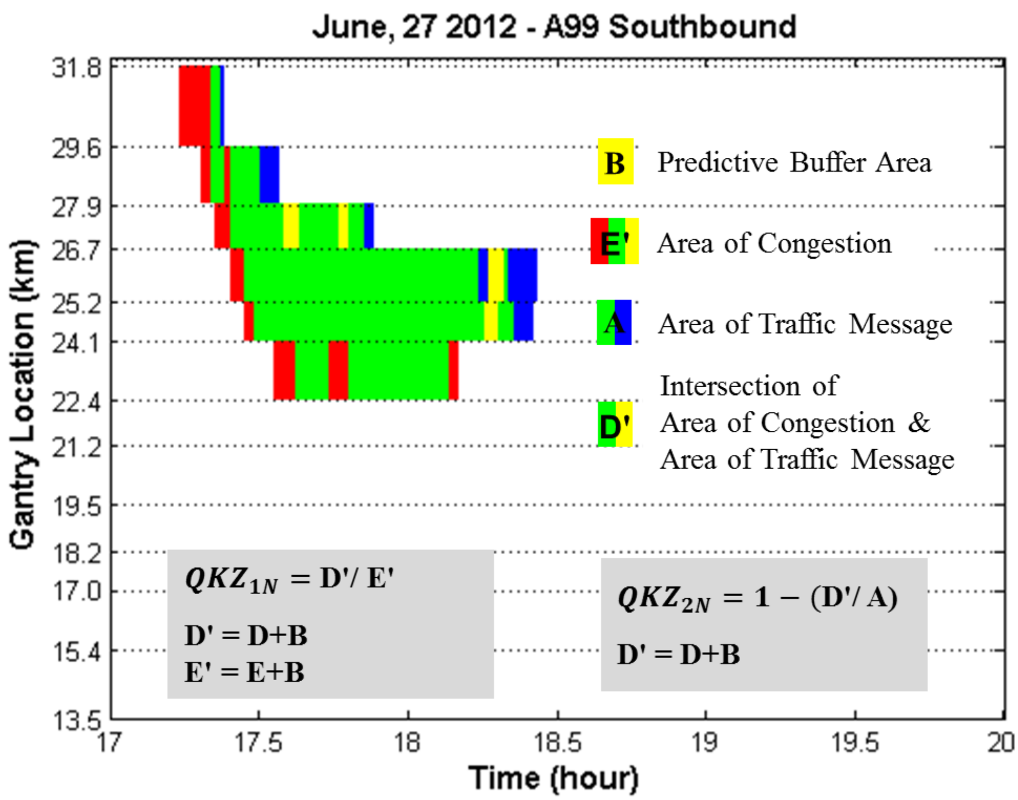



Figure 6.11: Estimation of $QKZ$ indexes with predictive buffer

$$D' = D + B \tag{6.3}$$

$$E' = E + B \tag{6.4}$$

The introduction of the predictive buffer improves the detection rate and decreases the false alarm rate. In situations where $D'$ and $E'$ match exactly in space and time, the indexes do not change from the original QKZ method ($B = 0$). Again, if the false alarm is at the downstream end of real congestion, $B$ does not come into the equation.

# Chapter 7

# Data Evaluation – Applying the Developed Methods

The methods developed in this research work have been applied to real world problem to prove their applicability. Results from the case study on the different features of VSL systems as well as comparison between VSL and RTTI are presented in this chapter. Inferences and discussions, based on the evaluation, are also made.

Data for three days for each month of the study period (i.e., April - July 2012) were randomly chosen and analyzed in detail to test the developed methods. However, the selection was done to satisfy the following condition:

- there should be congestion on the corridor under consideration for the selected day.

The study location and data, are as previously discussed in chapter 4.

## 7.1 Incident Detection Analysis

The traffic state was reconstructed and the TGT based on minimum speeds generated as in the example of Figure 5.2 and Figure 5.4, respectively. The threshold for congestion was set to the VSL system's defined threshold of 60 km/h. This will be discussed in subsection 7.4.2. The two matrices, Min-TGT and the message signs were then matched. Considering the fact that free flow traffic prevails during most part of the day, and that a provider reporting only free flowing traffic will score high ratings because non detections of congestion will be "masked," all events where both speeds (GT and Min-TGT) were above the congestion threshold were left out of the evaluation. For example, Figure 7.1 shows the superimposition of the two matrices for July 26, 2012. The color green represents the proportion of congestion area that was covered by the system's messages, blue represents the proportion of VSL messages that lies outside the congested area, and red represents congested area that was not matched by the system's messages. As shown in Table 7.1, values of $66.1\% - 85.2\%$ were obtained for $QKZ_1$ and $6.0\% - 44.8\%$ for $QKZ_2$. These resulted in grades of "A-C" on the quality diagram (see Figure 7.2) which are practically good.

It is realized from Figure 7.1 that a substantial part of missed detections occur at queue tails. This trend was also observed in almost all the other days studied. Missed detections at queue tails are very dangerous particularly in Germany where there is no speed limit on freeways. Again, as can be seen in Figure 7.1, significant proportion of false alarms occur at the commencement of the congestion and also immediately after the congestion has dissipated. Timely reaction by the system to changes in traffic conditions seems to be a problem. The implemented algorithm at the study location prevents volatility of the system by updating only at certain time interval. This partly explains why there is significant FAR at the onset of congestion and immediately after it has dissolved. This study affirms the finding by [146] of the need for a model to predict congestion before the onset of actual congestion.

Table 7.1: Evaluation of incident detection of VSL

| **Date** | $QKZ_1$ (%) | $QKZ_2$ (%) | **Grade** |
|---|---|---|---|
| 1-Apr-12 | 67.7 | 33.5 | C |
| 19-Apr-12 | 66.1 | 12.6 | B |
| 27-Apr-12 | 81.4 | 22.5 | B |
| 10-May-12 | 74.3 | 44.8 | C |
| 22-May-12 | 71.7 | 13.7 | B |
| 24-May-12 | 71.3 | 15.4 | B |
| 11-Jun-12 | 72.0 | 25.1 | B |
| 15-Jun-12 | 70.6 | 16.3 | B |
| 27-Jun-12 | 79.7 | 11.8 | B |
| 5-Jul-12 | 74.9 | 26.0 | B |
| 9-Jul-12 | 85.2 | 13.4 | A |
| 26-Jul-12 | 78.9 | 6.0 | A |

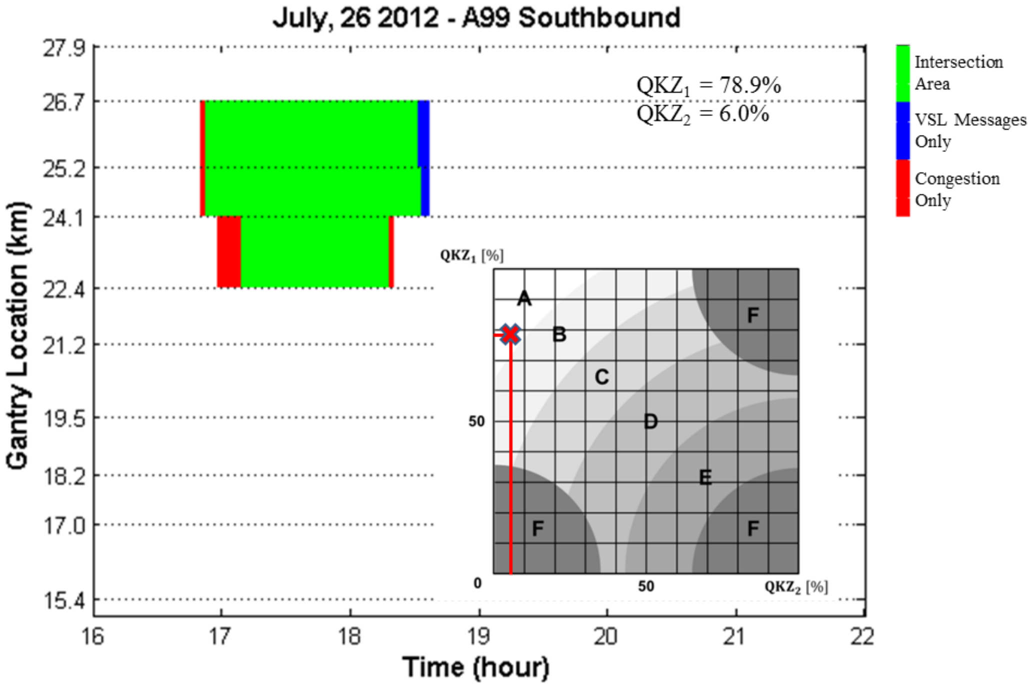



Figure 7.1: Superimposition of Min-TGT and message signs

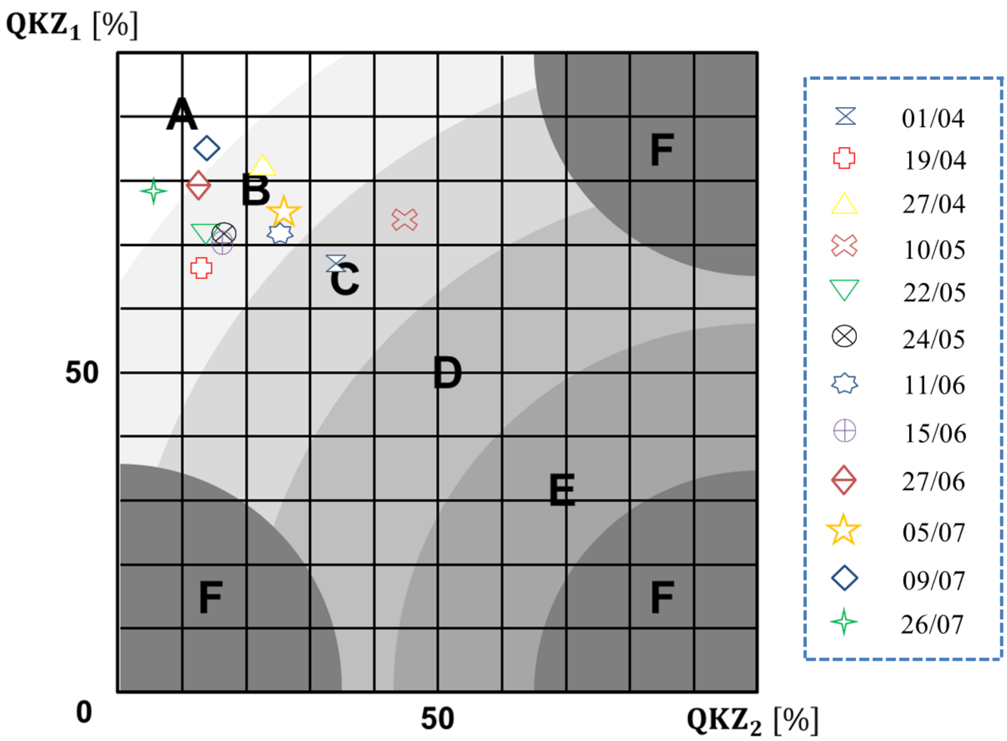



Figure 7.2: Performance of incident detection on the QKZ scale

## 7.2 Warning Efficiency Analysis

Virtual trajectories were generated at 5 minute intervals from the ASM plot using the modified FSB method. The scenarios used as well as the weightings adopted are as shown in Table 5.1. Again, scenario type A.3 (no warning in free flow traffic) was excluded as it could not be assigned to any of the areas in the context of the QKZ method, and will render false alarms unnoticed in the overall analysis. In fact, scenario type A.3 constituted 98% of all scenarios. Excluding scenario A.3 from the analysis also ensured that the system does not get evaluated when it was deactivated. From the computation, weighted values of 64.3% − 83.1% and 6.7% − 58.6% were obtained for $QKZ_1$ and $QKZ_2$, respectively (see Table 7.2). Again, these resulted in rating the VSL system's efficiency in warning as "A-C" on the quality scale (see Figure 7.3) which is practically good.

The distribution of the different scenarios considered in the analysis is as shown in Figure 7.4. Giving appropriate warning in congested regions (scenario type C.1) constituted over one-half (51.8%) of all scenario types considered. The other appropriately issued warning scenarios, at least the last two upstream gantries before congestion displaying warnings within recommended distance (B.4) and warning at last gantry before congestion (B.2), represented 7.0% and 1.2%, respectively. The second most frequently encountered scenario type, warning in free flowing traffic (scenario type A.1), constituted 13.1%. This, has the potential of denting the credibility of the system and cause drivers to disregard signs in the future. Interrupted warning sequence (scenario type B.5) was not encountered at all in the days analyzed whereas warning distance being too far (A.2), which drivers may consider as false alarm, was represented in only 0.2% of the cases. The proportion of the different scenarios which constituted missed detections were, no warning at last gantry before congestion (B.1, 7.4%) or the warning distance being too short to allow enough reaction time (B.3, 9.2%), and no warning in congestion (C.2, 10.2%). Efforts must be put in place to address scenario types B.1 and B.3 as it may present safety problems to motorists and their passengers.

### Incident Detection versus Warning

Comparing the $QKZ_1$ and $QKZ_2$ values for both automatic incident detection and warning efficiency, it is established that the former performed slightly better than the latter. This is seen clearly in Figure 7.2 and Figure 7.3. For incident

Table 7.2: Evaluation of warning capability of VSL

| Date | $QKZ_1$ (%) | $QKZ_2$ (%) | Grade |
|---|---|---|---|
| 1-Apr-12 | 66.6 | 42.1 | C |
| 19-Apr-12 | 64.3 | 18.2 | B |
| 27-Apr-12 | 75.0 | 32.3 | B |
| 10-May-12 | 68.1 | 58.6 | C |
| 22-May-12 | 69.2 | 18.2 | B |
| 24-May-12 | 77.7 | 18.4 | B |
| 11-Jun-12 | 70.7 | 38.8 | C |
| 15-Jun-12 | 64.7 | 22.3 | B |
| 27-Jun-12 | 71.7 | 21.8 | B |
| 5-Jul-12 | 67.1 | 40.4 | C |
| 9-Jul-12 | 83.1 | 6.7 | A |
| 26-Jul-12 | 76.3 | 9.9 | B |

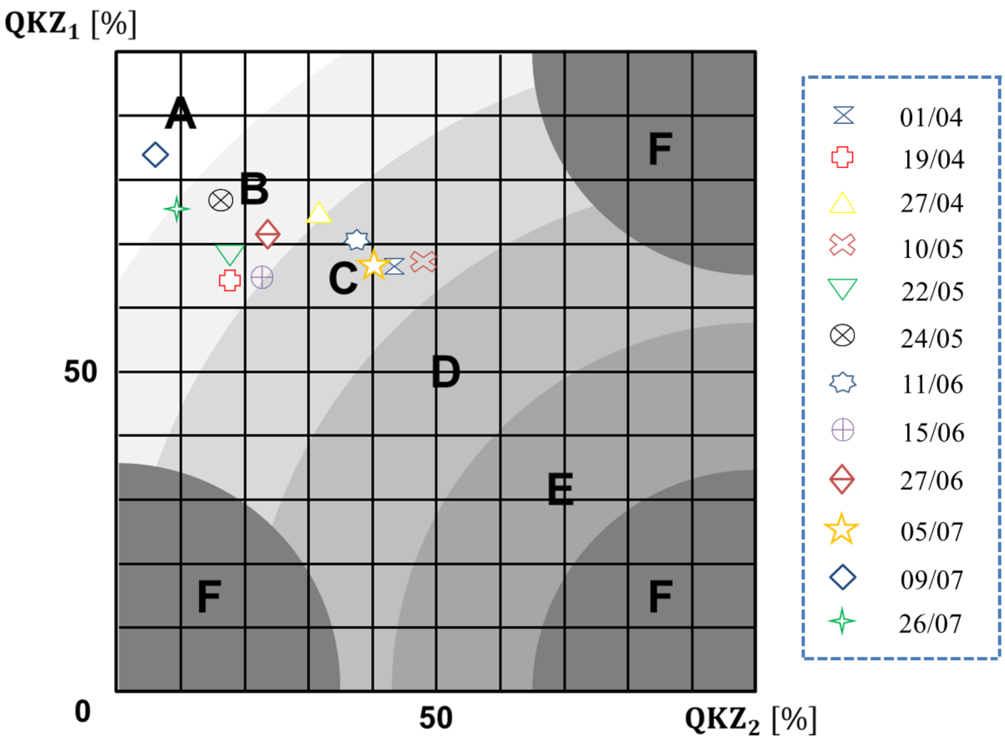



Figure 7.3: Performance of warning efficiency on the QKZ scale

detection, 2 out of the 12 days considered scored “A,” 8 out of 12 scored “B,” and 2 out of the 12 days scored “C.” In contrast to warning efficiency assessment, 1 out of the 12 days scored “A,” 7 out of 12 scored “B,” and 3 out of 12 were graded as “C.”

This result was as expected as the warnings rely on alarms from incident detection. However, the difference indicates that there were still some false warning alarms

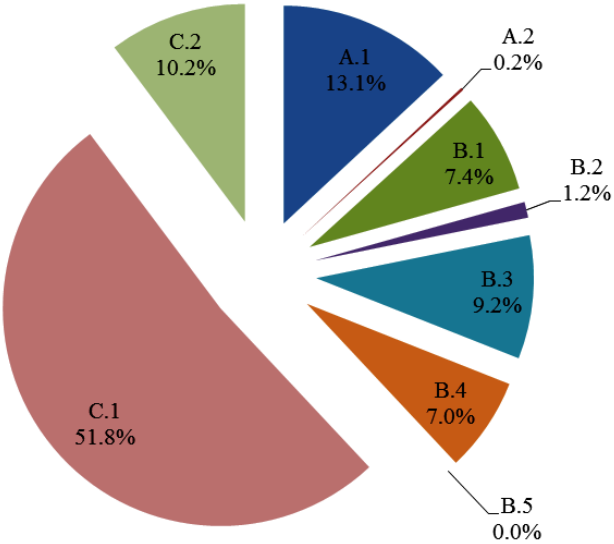



Figure 7.4: Proportion of warning scenario types

even after correct detections. Evaluating these two features independently makes it easier to know where problems are originating from in the system.

## 7.3 Harmonization Analysis

Throughout this dissertation, data from April-July 2012 have been used. But additional data that are used purposely for speed differential analysis have to be explained. In order to evaluate the ability of the system in reducing speed variance under harmonization assessment, data for periods when the system was off were needed so that comparison can be made between the "on" and "off" cases. Data for the 41 day period October 15–25, and November 1–30, 2003 were also available. On October 25 and November 1–10, 2003, the VSL system was off although traffic data were available. Though the 2003 data are fairly dated relative to the 2012 data, and traffic characteristics might have changed, it was included to aid in the analysis of the "on" and "off" cases. Data for the "off" case is not available for 2012. It is also worth mentioning that whereas the 2012 data covered approximately 34 km with 25 detector stations, the 2003 covered 16 km with 14 detector stations (detector numbers 060 – 235 in Figure 4.2). With the exception of speed variance which was assessed using both the 2003 and 2012 data, all other features were assessed with the 2012 data.

### 7.3.1 Evaluating Speed Variance in Synchronized Traffic

The GT for speed and flow data were reconstructed as in Figure 5.2 and Figure 5.14. Next, the metastable traffic state needed to be identified. Therefore, thresholds for speed and volume required for the traffic states classification were defined. For speed, the system's threshold of what constitute congestion was used. That is, $V_{crit}$ was set to 60 km/h. Traffic stream is mostly heterogeneous comprising of different categories of vehicles with varying dimensional and operational characteristics. Therefore, before the threshold for flow was defined, the different vehicle categories were expressed in equivalent units. In order to convert the traffic stream composed of different vehicle types into an equivalent traffic stream, trucks and buses were converted to their passenger car equivalent (PCE) or passenger car unit (PCU) by multiplying their numbers by a factor of 3 [130]. Traffic flows were averaged over all lanes (taking into account when the hard shoulder lane was either opened or closed) to obtained the flow per lane. A value of $q_{min}$ of 600 vehicles/h/lane was used in the analysis. The GT for speed and flow data were then superimposed to obtain the different traffic states (see example in Figure 5.16 for the GT speeds of Figure 5.2 and GT flow of Figure 5.14). The aggregated standard deviation speeds for all lanes were used. In this regard, speed deviation across lanes (lateral speed harmonization) is measured. The coefficient of variation at detector stations within the metastable traffic state regions were then calculated according to Equation 5.15 and are as presented in Table 7.3. It is worth mentioning that a sensitivity analysis was carried out on the flow threshold used in identifying the traffic states. Values experimented with included 800, 1000 and 1200 vehicles/h/lane. It was observed that the CV shrinks across the board as the traffic flow increases (see Appendix A). Finally, Welch's $t$-test (or unequal variances $t$-test) [165–167] was performed in MATLAB to test the significance of any observed changes in the CV at the 95% confidence level.

From the analysis, there was no statistically significant difference ($p = 0.231$) between the periods when the VSL system was "on" and when it was "off" in 2003. That is, the system had not substantially reduced speed deviations. Nissan [145] noticed that the success of dynamic motorway traffic management depends to a large extent on how the drivers respond to the displayed VSL and their interaction with other vehicles. Failure of a system to effectively manage traffic may be due to a high non-compliance rate. Riggins et al. [164] studied the driver compliance level at the test location (autobahn A99). The study compared the displayed VSL to the ground truth speed measured by loop detectors. It was established that approximately 58% of traffic on the corridor was moving above the displayed variable speed limits while the system was active. The high level of non-compliance to the displayed speed limits may partly explain why no significant difference was found between the "on" and "off" cases in 2003. Conversely, the study found a significant difference ($p < 0.001$) in the 2003 and 2012 results when the VSL system was on. There was also a marked difference ($p < 0.001$) in the "on" case in 2012 and the "off" case in 2003. However, this cannot be attributed to the system as it might be due to changes in the traffic characteristics resulting from the time difference, or due to recalibration or change in the implemented harmonization algorithm.

Table 7.3: Results of coefficient of variation

| **Date 2012** | **CV "On"** | **Date 2003** | **CV "On"** | **Date 2003** | **CV "Off"** |
|---|---|---|---|---|---|
| 1-Apr | 9.7 | 15-Oct | 9.9 | 25-Oct | 10 |
| 19-Apr | 9.9 | 17-Oct | 10 | 1-Nov | 10.1 |
| 27-Apr | 9.2 | 19-Oct | 10 | 2-Nov | 10.4 |
| 10-May | 9.4 | 22-Oct | 10.1 | 3-Nov | 11.1 |
| 22-May | 9.7 | 24-Oct | 9.8 | 4-Nov | 10.9 |
| 24-May | 8.7 | 11-Nov | 11.9 | 5-Nov | 10.6 |
| 11-Jun | 9.4 | 16-Nov | 11.2 | 6-Nov | 10.9 |
| 15-Jun | 9.2 | 19-Nov | 10.9 | 7-Nov | 10.8 |
| 27-Jun | 9.6 | 23-Nov | 11.2 | 8-Nov | 12.5 |
| 5-Jul | 8.7 | 26-Nov | 11.1 | 9-Nov | 11.1 |
| 9-Jul | 8.8 | 28-Nov | 9.1 | 10-Nov | 11.4 |
| 26-Jul | 8.9 | 30-Nov | 10.9 | - | - |
| **Average** | 9.3 | - | 10.5 | - | 10.9 |

### 7.3.2 Consistency Assessment

Trajectories were generated at 5-minute intervals and then followed to simulate the speed limits drivers would have encountered. The experiences of drivers were grouped into the various scenario types (see subsection 5.3.3) and consistency calculated according to Equation 5.16 and Equation 5.17. The results of the case study are as presented in Table 7.4. From the evaluation, successful consistency rates ranged from 90.1% to 100.0% with an average of 93.8% for the days studied which can be said to be practically good. However, the performance of the system can still be improved to ensure smooth harmonization at all times. Figure 7.5 shows the distribution of the different scenario types encountered by drivers as they traverse the corridor. A total of 79% of all scenario types involved constant speed limits at consecutive gantries, gradual speed drops constituted 8%, and speed increments made up 7%. The roller coaster pattern and rapid speed drop constituted 4% and 2%, respectively. Roller coaster pattern wastes fuel, pollutes the environment and is seen as an indicator for unsafe driving. Driving at a steady speed under such circumstances should be the aim. Rapid speed drops may also result in rear-end collisions when witnessed at the tail of queues.

Table 7.4: Rates of successful consistency on autobahn A99 near Munich, Germany

| **Date 2012** | **Successful Consistency Rate (%)** |
|---|---|
| 1-Apr | 100.0 |
| 19-Apr | 93.8 |
| 27-Apr | 94.2 |
| 10-May | 95.7 |
| 22-May | 96.4 |
| 24-May | 91.8 |
| 11-Jun | 92.8 |
| 15-Jun | 93.4 |
| 27-Jun | 92.7 |
| 5-Ju | 90.1 |
| 9-Jul | 91.7 |
| 26-Jul | 93.5 |
| **Average** | **93.8** |

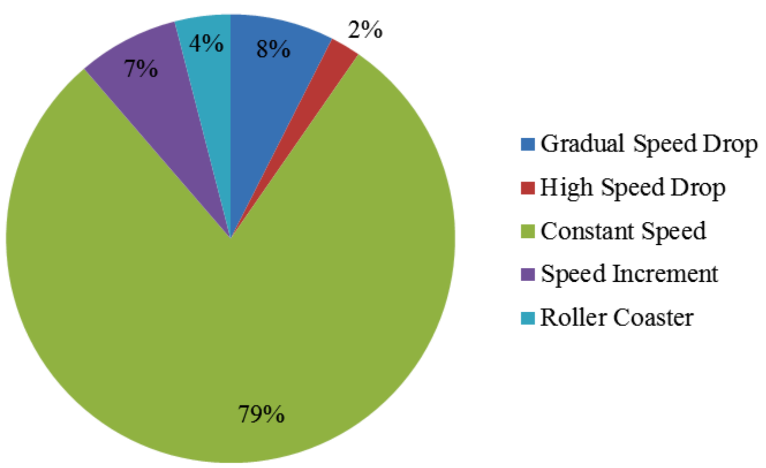



Figure 7.5: Proportion of consistency scenario types

### Speed Variance versus Consistency

A higher rate of successful consistency should imply a stronger harmonization. Therefore, the results from the speed variance and consistency analysis for the 2012 data were compared. From the assessment, no statistically valid relationship was established between the two approaches. This may also be attributed to the level of driver compliance. A higher rate of successful consistency should result in a lower standard deviation of speeds if speed limits are obeyed. Data from other sites need to be analyzed to verify the relationship between the two methods.

## 7.4 VSL versus RTTI

### 7.4.1 Qualitative Analysis

Firstly, the traffic state was reconstructed and the Min-TGT for VSL and RTTI generated. Next, the difference matrix between the minimum technical ground truth and the traffic information were created as in the example of Figure 6.6 for VSL and Figure 6.7 for RTTI for all the 12 days considered for the case study. From the difference matrix, histograms were created. Results of the frequencies of the differences between GT and the broadcast speeds are as shown in Table 7.5. As can be observed in Appendix B.1, for almost all days considered for VSL, the difference histograms had at least two peaks. One for vehicles traveling above the displayed speed limit and the other for vehicles traveling below the displayed speed limit. The histograms were positively skewed. In approximately 85% of the considered cases, the displayed speeds were within ±20 km/h of the ground truth speeds. For RTTI (see Appendix B.2), the histograms were unimodal and symmetric (mean ≈ median). In approximately 91% of the situations, the broadcast speeds were within ±20 km/h of the ground truth speeds.

The distribution of the deviation of the GT speeds from the displayed speeds of the VSL was not expected as drivers are required to travel at or below the displayed speed. A negatively skewed distribution would have been the expected result. This can be attributed to driver non-compliance to the displayed speed limit. However, this can also connote false alarm where the system displays speeds lower than the ground truth speed. For instance, displaying a VSL of 60 km/h for a GT situation of 100 km/h may dent the credibility of the system. This may result in undue delay

Table 7.5: Frequencies of differences between GT and broadcast information.

| | VSL (%) | | | RTTI (%) | | |
|---|---|---|---|---|---|---|
| **Date** | *±5* | *±10* | *±20* | *±5* | *±10* | *±20* |
| 1-Apr-12 | 60.3 | 79.6 | 96.2 | 49.0 | 76.2 | 95.5 |
| 19-Apr-12 | 15.7 | 40.8 | 85.9 | 36.7 | 63.8 | 92.5 |
| 27-Apr-12 | 12.5 | 51.7 | 92.1 | 36.8 | 65.7 | 93.9 |
| 10-May-12 | 12.3 | 41.9 | 86.7 | 32.4 | 63.3 | 92.4 |
| 22-May-12 | 14.6 | 39.1 | 86.7 | 36.5 | 63.5 | 92.7 |
| 24-May-12 | 14.8 | 34.2 | 78.6 | 32.1 | 57.7 | 87.7 |
| 11-Jun-12 | 10.3 | 32.3 | 81.0 | 34.0 | 61.2 | 90.7 |
| 15-Jun-12 | 12.4 | 38.4 | 92.2 | 41.9 | 68.5 | 93.6 |
| 27-Jun-12 | 12.4 | 36.5 | 86.5 | 34.3 | 60.8 | 91.0 |
| 5-Jul-12 | 13.1 | 27.1 | 77.0 | 26.8 | 50.6 | 85.3 |
| 9-Jul-12 | 9.9 | 24.2 | 71.4 | 30.5 | 55.0 | 85.8 |
| 26-Jul-12 | 12.5 | 39.9 | 88.6 | 33.9 | 61.7 | 93.8 |
| **Average** | **16.7** | **40.5** | **85.2** | **35.4** | **62.3** | **91.2** |

to motorists and cause drivers to ignore warnings in the future. RTTI providers, on the other hand, intend to estimate actual speeds in real-time. Therefore, it is not surprising that the distribution of the difference matrix is symmetrical. However, in the same way, for the situations where the broadcast speeds are higher than GT speeds, this may represent false alarm. Situations where the GT speeds are higher than the broadcast speeds may also represent missed detection which is harmful to traffic safety. Under such circumstances, the drivers are taken by surprise of the speed drop and may result in rear-end collisions. Although it was observed that the RTTI provider, often, broadcast higher speeds in congested regions when the space-time speed map was compared with its discretized GT (subsection 6.1.3), the deviations were, largely, within ±20 km/h as seen in Table 7.5.

The distributions of the deviations of the GT speeds from the broadcast speeds can give an indication of the performance of the different systems. However, no definite deductions can be made on the abilities of the systems to detect congestion and subsequently issue appropriate message. In order to achieve that what constitute congestion needs to be defined, measured in reality, and then compared to the displayed speeds. The quantitative assessment will examine this issue in depth. One important difference between the qualitative and quantitative comparative analysis needs to mentioned. Whereas the qualitative analysis included speeds in both congestion and free flowing conditions, the quantitative analysis focused on only congestion regions.

### 7.4.2 Quantitative Analysis

The traffic state was reconstructed (e.g., Figure 6.1) and the Min-TGT for VSL and RTTI generated as in the example of Figure 6.2 and Figure 6.3, respectively. The two matrices, Min-TGT and the displayed speeds, were then matched in each instance. It was envisaged that the critical speed used in defining congestion could have an influence on the adapted QKZ indexes with the predictive buffer. Therefore, different values (40, 50, 60, 70, 80, 90, and 100 km/h) for the critical speed were chosen based on past empirical findings [128, 149, 168] and used in the analysis. If the RTTI provider's and VSL system's defined thresholds for congestion are known, they must be used. However, different VSL algorithms and RTTI providers may be using different thresholds. With the speed threshold sensitivity analysis, the author hoped to achieve a quality index which will show a high detection and low false alarm rates. Results for the superimposition of the displayed VSL and RTTI and their respective Min-TGT, and the sensitivities of the indexes to the various critical speeds are presented in Appendices C.1 and C.2 for VSL and RTTI, respectively. Their performance on the QKZ quality diagram are also visualized in Appendices C.3 and C.4.

Generally, it was noticed that the quality indexes were dependent on the speed threshold used to define congestion. The following observations could be made regarding the speed thresholds on the performance of the two information sources:

- the performance of the VSL appears to increase from a threshold of 40 km/h to 60 km/h and then decrease again. That is, the optimal performance occurred at a speed threshold of 60 km/h. For speed thresholds above 60 km/h, the performance of the system on the quality scale appears to be less sensitive.

- the best performance of the RTTI appears to occur at a relatively higher speed threshold. It increases from a speed threshold of 40 km/h until 80 km/h and then decreases. The optimal performance was, therefore, observed at a threshold of 80 km/h.

In general, VSL information performed significantly better than RTTI when the two information sources where compared with the same speed threshold as can be seen on the QKZ scale in Appendix C.3 for VSL and Appendix C.4 for RTTI. Even when the results of the optimal performances of the systems are analyzed, the VSL system still outperforms RTTI. The better performance of the VSL system may be attributed to the following:

1. the relatively shorter distances between successive gantries of the VSL as compared to distances between TMC locations. The average distance between gantries was 1450 m whilst that of TMC locations was 2780 m. As was demonstrated earlier, higher resolution spatial referencing approximates better to the ground truth traffic situation.

2. the data source used to generate the GT traffic situation is the primary data source for the VSL system. A different data source, from what is used by the VSL system's service provider, would have allowed an objective assessment.

# Chapter 8

# Conclusions, Recommendations, and Future Research

Advanced traveler information system is viewed as an efficient way of managing the dynamic nature of traffic on freeways and urban arterial corridors. The main motivation of this dissertation was to determine inconsistencies, if any, between traffic information provided from different sources. The VSL system and RTTI data used by navigational devices were used as subjects for the study. The aforementioned issue, together with other relevant ATIS problems, have been largely addressed.

To answer the first research question, methods for assessing different components of VSL systems were developed. In previous VSL evaluation methods, the analysis do not differentiate between the features of VSL systems, particularly, its ability to automatically detect an incident before issuing an appropriate warning or otherwise and how these are related. Once the different components are isolated, it is easier to identify any problematic component of the system for remedial measures. The performance levels were then graded on a quality scale. Traditionally, in assessing the efficiency of VSL systems to harmonize traffic, absolute standard deviation of speed has been employed. In this thesis, the coefficient of variation of speeds was used as measure to make it more meaningful to compare data sets gathered from different detector stations. This study developed a method, taking into account predictive buffer areas, to answer the second research question. Earlier studies had considered predictive buffer regions, which are key component of optimal control strategies as false alarm. However, our understanding of optimal control approach indicates that this is not the case. In the current methods developed, the limitations faced by the traffic information providers were also taken into accounts by discretizing the ground truth traffic situation.

This final chapter contains a summary of all the methods developed and their application to real world problems. Recommendations on the current system are given and finally an outline for future research is provided.

## 8.1 Summary and Conclusions

The success of any traffic information system depends on the quality of the information provided. Accuracy of the information broadcast is very important for driver acceptance and subsequently their obeying the displayed messages. This can “make or break” the successful implementation of any ATIS. Therefore, the issue of quality traffic information provision is relevant to both the service provider and consumer.

Understanding of the processes of the different systems was key for developing the evaluation measures. Accordingly, the process chain of the VSL and RTTI were studied. VSL systems, primarily, use stationary detectors (e.g., inductive loops and radar detectors) in collecting their input data. RTTI providers, in addition to the stationary detectors, use mobile mechanisms (e.g., floating phone and floating car data), fuse the data, and use them as their input data. Mobile mechanisms of data gathering ensure that providers are able to collect traffic information at locations with no stationary detectors. The traditional stationary detectors are more expensive to install and maintain. Using data from different sources and fusing them have the advantage that: gaps within the data are closed. Control algorithms for ATIS were also considered. Aside dealing with congestion globally and the coordination of traffic controls, prediction of the evolution of congestion is required for optimal control. This is because, the effect of traffic information on flow is not instantaneous. Consequently, if congestion can be predicted, then remedial measures can be put in place.

Methods for evaluating VSL systems were developed and presented. VSL system is expected to detect incidents and take measures to carry out any or all of the following: avoid crashes, postpone or alleviate congestion by providing warning messages, and harmonize traffic by reducing speed differences between vehicles and among lanes. As VSL systems may be implemented with different control strategies, an approach for assessing the different features of the system independently was adopted. Methods for assessing three (3) features, namely:

1. incident detection,
2. warning, and
3. harmonization efficiency

have been discussed. Because warning and harmonization algorithms rely on incident detection for reaction, it was important to evaluate them separately in order to make it easier to isolate problematic components of the system.

Incident detection was evaluated by first reconstructing the traffic state from point detector data to obtain a continuous spatio-temporal speed function, and discretizing the speed fields to correspond with the positions of the VSL gantries. By defining a speed threshold for congestion, the discretized speed information was matched with a spatio-temporal representation of variable messages displayed to drivers. Indexes developed from the ratio of the space-time coverage of ground truth congestion, and congestion information from the VSL system was then used to grade the system on the QKZ quality scale.

For warning efficiency, virtual trajectories were generated on the bases of the reconstructed traffic state to simulate vehicles. The generated trajectories were then superimposed on the spatio-temporal matrix representing the displayed variable messages and a determination was made as to whether a driver experienced appropriate and timely warnings or not. Based on the distance of the warning and traffic condition, scenarios were identified and weightings awarded depending on the importance of the scenario on safety. Warning efficiency was also graded in the context of the QKZ method. This was done to enable comparison of incident detection and warning efficiency.

The advantages of the incident detection and warning efficiency methods presented here over existing methods are that:

- evaluating the two features independently makes it easier to know where problems are originating from in the system,
- both methods lead to comparable quality indexes, and
- the performance levels are also graded on a quality scale.

Two methods for evaluating harmonization capabilities of VSL systems were proposed. The methods were based on the ability of the VSL system to:

1. reduce speed differentials and
2. convey a coherent picture of the traffic situation and prepare drivers progressively for a downstream bottleneck, that is, consistency.

The ability of the system to reduce speed variance was evaluated by reconstructing the GT for speed and flow, superimposing them, and classifying the different traffic states, identifying the metastable traffic conditions, and determining whether the system has been able to minimize speed variation. Speed differential evaluation was done only in the metastable traffic state since application of VSL to harmonize traffic is deemed beneficial only under such situations. The deviation in speeds was measured using the coefficient of variation. Consistency, on the other hand, was studied by tracking vehicles and observing the variations in the displayed speed limits as drivers traverse a route. This was made possible by first reconstructing the traffic state and generating virtual trajectories to simulate vehicles. The different scenarios encountered by drivers were categorized, and finally a check on consistency made based on successful and failed consistency rates. It is envisaged that the different methods presented for harmonization can be used in the following ways:

- The speed differential method could be used to assess lateral speed harmonization.
- The consistency approach can be used to measure longitudinal speed harmonization.
- Again, the consistency approach could be employed as a quick check in determining the potential of VSL systems to harmonize traffic flows, particularly, in new installations.

Before the quantitative evaluation of the two different sources of information was carried out, a qualitative analysis was done to understand the characteristics of the data from the two sources. The assessment was made by obtaining the differences in speeds between the discretized space-time representation of reality, reconstructed from inductive loop detector data, and the space-time traffic information posted by the VSL/RTTI. The discretization ensured that the method takes into accounts, limitations faced by the providers in broadcasting the information. The difference matrix gave an idea of how close or otherwise the broadcast information is from the GT. The difference matrix was then illustrated in a histogram which showed the distribution of the broadcast information around the GT. From the histogram, inferences were drawn on the performance of the systems. However, no valid conclusion could be made from the qualitative test.

Optimal control approaches include the prediction of congestion in their control strategies. Congestion prediction, if done accurately, will have a positive influence on traffic management. This study adapted and introduced a predictive buffer to the QKZ method to quantitatively compare and grade the two information sources. The QKZ method deals with the congestion areas of traffic reality to the congestion areas of traffic information without any regard as to whether a traffic message was intended as congestion forecast or not. In this study, this was taken into account. The predictive buffer was considered as areas of traffic information which could be taken as advance warning area, or rightly predicting and giving congestion information prior to the onset of actual congestion, which otherwise would have been taken as a false alarm, in the evaluation. In this way, traffic information providers implementing optimal control approaches are evaluated fairly. To quantitatively grade the quality levels, the QKZ method was adapted and employed in the evaluation.

The developed methods were tested in a case study on the autobahn A99 near Munich, Germany. The study location was approximately 33.5 km long freeway with a VSL system installed. It is a dynamic VSL system which is mostly activated during daytime and off at nighttime when traffic flow is low. On this same stretch of road, there were TMC locations for which traffic information is broadcast. RTTI are broadcast throughout the entire day. Data for the four month period April-July, 2012 for both the VSL and RTTI were available.

The result for the VSL evaluation showed a reasonably good performance of the system for the days considered. Incident detection and warning efficiency scored grades of between "A" and "C" on the quality diagram. However, in the case of incident detection, a significant amount of missed detections occurred at queue tails, at the commencement of congestion, and also immediately after congestion had dissolved. The majority of missed detections for warning capability involved situations in which there were no warning before congestion or warning distances were too short. Comparing the $QKZ_1$ and $QKZ_2$ values for incident detection and warning efficiency showed that the former performed slightly better. The difference indicated that there were still some false warning alarms even after correct detections justifying why these features should be assessed independently.

In assessing harmonization, the study did not find a statistically significant difference in speeds in the metastable traffic state regions when the VSL system was on and when it was switched off. This was, however, partly attributed to the level of driver non-compliance of the displayed speeds as driver reaction to the displayed speed limits has been established to have an effect on the performance of VSL systems. Consistency, on the other hand, was found to have performed practically well on the stretch, but can still be improved upon. The most predominant scenario type encountered by drivers was constant speed at consecutive gantries. This was followed by gradual speed drop and speed increment. From the assessment, no statistically valid relationship was found between speed differential and consistency approaches. This finding was contrary to expectation as a higher rate of successful consistency should result in a lower speed differential.

The VSL system on the autobahn A99 was quantitatively compared with the traffic information broadcast by a private provider taking into consideration the predictive buffer areas. It was initially assumed that the speed threshold used to define congestion will have an effect on the grading of the different systems. Consequently, a sensitivity analysis was done on the speed threshold. It was shown that, generally, the VSL information on the road corridor performed better than the RTTI from the private provider. The better performance of the VSL system was attributed to: the shorter distances (i.e., high spatial referencing resolution) between gantries of the VSL system as compared with the distances between TMC locations. The data used to reconstruct the GT traffic situation was also identified to be a contributory factor. The GT data source was the same as the input data for the VSL. The study also identified that these information from the different sources may be using different thresholds to define congestion.

## 8.2 Recommendations

There is no doubt that advanced traveler information systems can play a major role in present-day traffic management. However, measures must be put in place by the service providers to ensure quality of the information provision. From the methods developed and subsequent discussions above, recommendations listed below have been made to help improve upon the current traffic information systems:

- Optimal control strategy must be the preferred control approach: This study affirmed the findings of earlier studies of the need for a model to predict congestion before the commencement of congestion. From the analysis, significant proportion of missed detections occurred at queue tails indicating an issue with the timely reaction of the system. An accurate prediction of the evolution of congestion will ensure timely measures to improve traffic flow and safety on our roads.

- Resolution of spatial referencing of ATIS (i.e., TMC segments) should be increased: As has been proven in this research, representing long distances with a single speed to depict the true traffic situation on a segment is challenging. Shorter TMC segments approximate better to reality. Therefore, TMC segments should be made practically as short as possible. For RTTI providers, the use of OpenLR technology should eliminate this challenge. However, for VSL systems, shorter spacing between gantries will improve upon their quality.

- There is the need for traffic information providers to synchronize their definitions of what constitute an incident: This recommendation may apply to traffic information providers who use color coded maps to represent the traffic situation. Uniformity in the color maps will make it easier for motorists and commuters to interpret the traffic situation and remove ambiguity. The conditions and thresholds for each color (incident) need to be defined across the board for all providers.

## 8.3 Future Research

The data available for this study, methods developed, and subsequent case studies have revealed limitations in some of the approaches used and suggested directions for future research. The suggestions, described below, may be worth considering by researchers working in the area of ATIS to help them improve upon their works.

### Data for Ground Truth Reconstruction

The first issue concerns with the data used to generate the ground truth speed. Stationary detector data is the input data source for the VSL system at the study site. This data source was used in the ground truth reconstruction, employed as a referencing frame, against which both the VSL and RTTI were measured. The detector data was used because, at the moment, there is no better source available. In future, an independent data source should be used. This could be from a mobile mechanism such as floating car or phone data. However, the number of probes should be representative (statistically valid) of the traffic flow on the road. In this way, a fair assessment will be achieved for both the VSL and RTTI.

### Data Transmission Delay

This research work, primarily, used traffic information data, which has been displayed on the gantry of the VSL or the navigation device. Apparently, there may be delays in the relay of the information from one stage of the process chain to the other. This means that the information shown on a gantry or displayed on the screen of a navigation device may not be for the time it was intended for. Delays from the data collection stage, processing, and transmission of the information to the end user were not taken into consideration in this study. It is recommended that, in future research, this should be taken into accounts. This will help understand the contribution of delay in data transmission to the quality of traffic information.

### Relationship between Speed Differential and Consistency

Although the two methods used in evaluating harmonization is theoretically sound, no statistically valid relationship could be found. The consistency approach, was motivated by the fact that systematic, consecutive variation in the displayed speeds should result in reduced speed differentials. Unfortunately, this hypothesis could not be confirmed at the study location. The method should be applied to data from other VSL installations to verify, if indeed, a relationship exist between the two approaches.

# List of Figures

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# List of Acronyms

| | |
|---|---|
| AI | Artificial Intelligence |
| ASDA/FOTO | Automatische Staudynamikanalyse/Forecasting of Traffic Objects |
| ASM | Adaptive Smoothing Method |
| ATIS | Advanced Traveler Information System |
| ATM | Active Traffic Management |
| AVL | Automatic Vehicle Location |
| CBR | Case-Based Reasoning |
| CCTV | Closed-circuit Television |
| Cebr | Centre for Economics and Business Research |
| CMS | Changeable Message Signs |
| CV | Coefficient of Variation |
| DAB | Digital Audio Broadcasting |
| DR | Detection Rate |
| DSL | Dynamic Speed Limit |
| DTM | Dynamic Traffic Management |
| DynaMIT | Dynamic network assignment for the Management of Information to Travelers |
| DYNASMART | Dynamic Network Assignment Simulation Model for Advanced Road Telematics |
| EU | European Union |
| FAR | False Alarm Rate |
| FCD | Floating Car Data |

| | |
|---|---|
| FCR | Failed Consistency Rate |
| FFT | Fast Fourier Transform |
| FPD | Floating Phone Data |
| FSB | Filtered Speed-Based |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| GT | Ground Truth |
| HCM | Highway Capacity Manual |
| ICT | Information and Communication Technology |
| IMTI | Integrated Multimodal Travel Information |
| ITS | Intelligent Transport System |
| KPI | Key Performance Indicator |
| Min-TGT | Minimum Technical Ground Truth |
| NDW | National Databank Warehouse |
| PCE | Passenger Car Equivalent |
| PCU | Passenger Car Unit |
| PNT | Positioning, Navigation and Timing |
| QBENCH | Quality Benchmark |
| QFCD | Quality Evaluation Based on Floating Car Data |
| QKZ | Qualitätskennziffer |
| RDS | Radio Data System |
| RTTI | Real-Time Traffic Information |
| RWIS | Remote Weather Information System |
| SCR | Successful Consistency Rate |
| SD | Standard Deviation |
| SLA | Service Level Agreement |
| SMS | Short Messaging Service |

| | |
|---|---|
| SVR | Support Vector Regression |
| TMC | Traffic Message Channel |
| TPEG | Transport Protocol Expert Group |
| TTS | Total Time Spent |
| UK | United Kingdom |
| USA | United States of America |
| USDOT | United States Department of Transportation |
| VSL | Variable Speed Limit |
| xFCD | Extended Floating Car Data |

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# Appendix A

# Sensitivity Analysis of Flow Threshold on CV

## A.1 CV - 800 vehicles/h/lane

Results of coefficient of variation - 800 vehicles/h/lane

| **Date 2012** | **CV "On"** | **Date 2003** | **CV "On"** | **Date 2003** | **CV "Off"** |
|---|---|---|---|---|---|
| 1-Apr | 9.7 | 15-Oct | 9.5 | 25-Oct | 9.4 |
| 19-Apr | 9.9 | 17-Oct | 9.6 | 1-Nov | 9.7 |
| 27-Apr | 9.0 | 19-Oct | 9.3 | 2-Nov | 9.9 |
| 10-May | 9.2 | 22-Oct | 9.7 | 3-Nov | 10.7 |
| 22-May | 9.6 | 24-Oct | 9.5 | 4-Nov | 10.5 |
| 24-May | 8.6 | 11-Nov | 11.5 | 5-Nov | 10.5 |
| 11-Jun | 9.3 | 16-Nov | 10.8 | 6-Nov | 10.5 |
| 15-Jun | 8.9 | 19-Nov | 10.5 | 7-Nov | 10.5 |
| 27-Jun | 9.4 | 23-Nov | 10.7 | 8-Nov | 12.0 |
| 5-Jul | 8.7 | 26-Nov | 10.5 | 9-Nov | 10.7 |
| 9-Jul | 8.6 | 28-Nov | 8.9 | 10-Nov | 11.0 |
| 26-Jul | 8.7 | 30-Nov | 10.5 | - | - |
| **Average** | 9.1 | - | 10.1 | - | 10.5 |

## A.2 CV - 1000 vehicles/h/lane

Results of coefficient of variation - 1000 vehicles/h/lane

| **Date 2012** | **CV "On"** | **Date 2003** | **CV "On"** | **Date 2003** | **CV "Off"** |
|---|---|---|---|---|---|
| 1-Apr | 9.7 | 15-Oct | 8.9 | 25-Oct | 9.0 |
| 19-Apr | 9.6 | 17-Oct | 9.1 | 1-Nov | 9.4 |
| 27-Apr | 8.7 | 19-Oct | 9.0 | 2-Nov | 9.5 |
| 10-May | 8.9 | 22-Oct | 9.2 | 3-Nov | 10.3 |
| 22-May | 9.4 | 24-Oct | 9.1 | 4-Nov | 10.0 |
| 24-May | 8.5 | 11-Nov | 11.0 | 5-Nov | 10.0 |
| 11-Jun | 9.1 | 16-Nov | 10.5 | 6-Nov | 9.9 |
| 15-Jun | 8.6 | 19-Nov | 10.2 | 7-Nov | 10.0 |
| 27-Jun | 9.1 | 23-Nov | 10.5 | 8-Nov | 11.7 |
| 5-Jul | 8.6 | 26-Nov | 10.1 | 9-Nov | 10.5 |
| 9-Jul | 8.3 | 28-Nov | 8.6 | 10-Nov | 10.5 |
| 26-Jul | 8.3 | 30-Nov | 10.3 | - | - |
| **Average** | 8.9 | - | 9.7 | - | 10.1 |

## A.3 CV - 1200 vehicles/h/lane

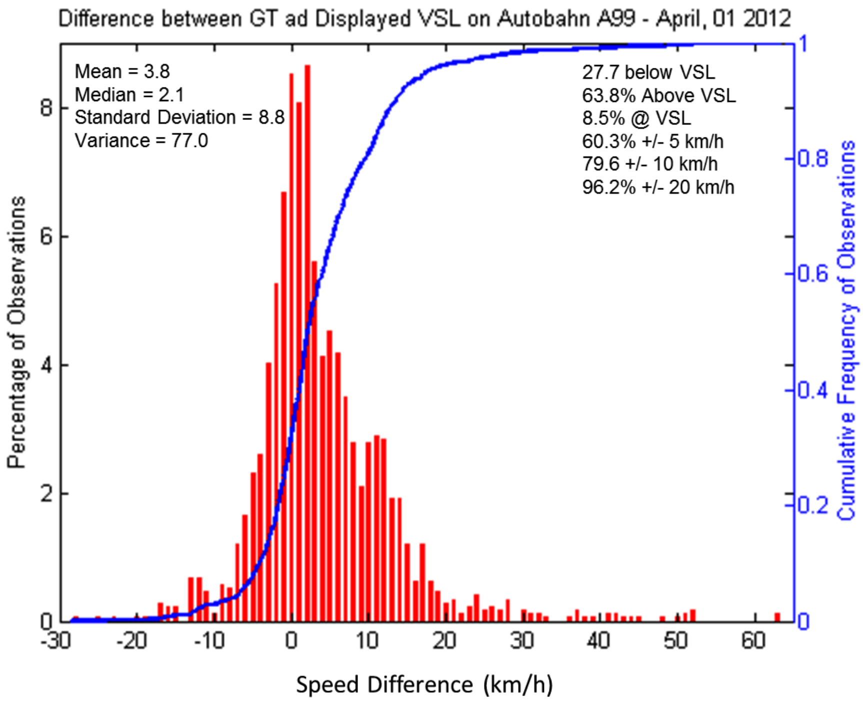
Results of coefficient of variation - 1200 vehicles/h/lane

| **Date 2012** | **CV "On"** | **Date 2003** | **CV "On"** | **Date 2003** | **CV "Off"** |
|---|---|---|---|---|---|
| 1-Apr | 10.9 | 15-Oct | 8.4 | 25-Oct | 8.8 |
| 19-Apr | 9.1 | 17-Oct | 8.6 | 1-Nov | 9.1 |
| 27-Apr | 8.6 | 19-Oct | 8.7 | 2-Nov | 9.2 |
| 10-May | 8.8 | 22-Oct | 8.8 | 3-Nov | 9.9 |
| 22-May | 9.0 | 24-Oct | 8.7 | 4-Nov | 9.6 |
| 24-May | 8.4 | 11-Nov | 10.6 | 5-Nov | 9.5 |
| 11-Jun | 8.8 | 16-Nov | 10.2 | 6-Nov | 9.2 |
| 15-Jun | 8.3 | 19-Nov | 9.8 | 7-Nov | 9.6 |
| 27-Jun | 8.8 | 23-Nov | 10.2 | 8-Nov | 11.5 |
| 5-Jul | 8.4 | 26-Nov | 9.5 | 9-Nov | 10.4 |
| 9-Jul | 8.1 | 28-Nov | 8.2 | 10-Nov | 10.0 |
| 26-Jul | 8.2 | 30-Nov | 10.1 | - | - |
| **Average** | 8.8 | - | 9.3 | - | 9.7 |

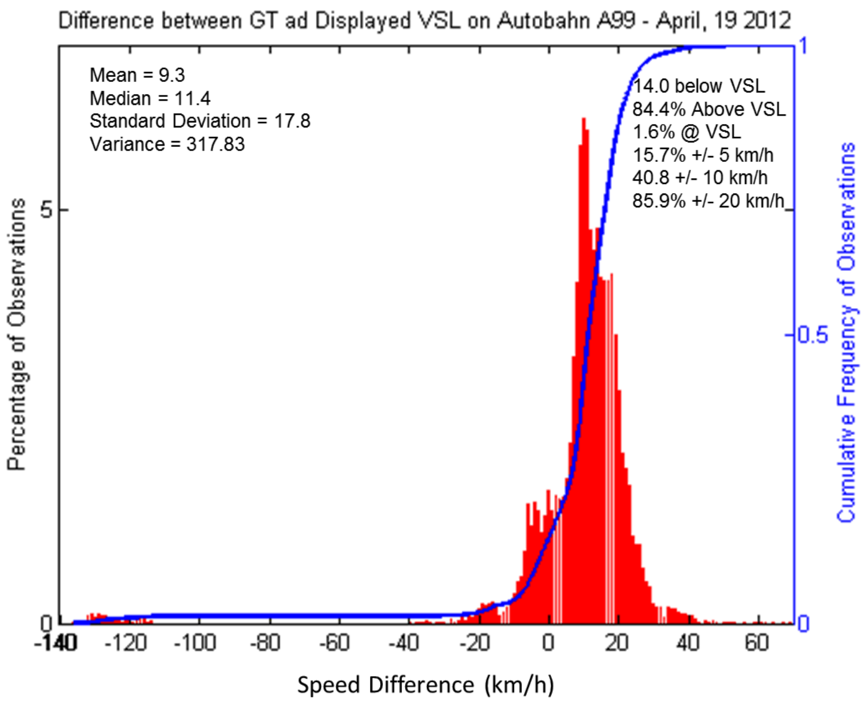
# Appendix B

# Distribution of Difference between GT and Traffic Information

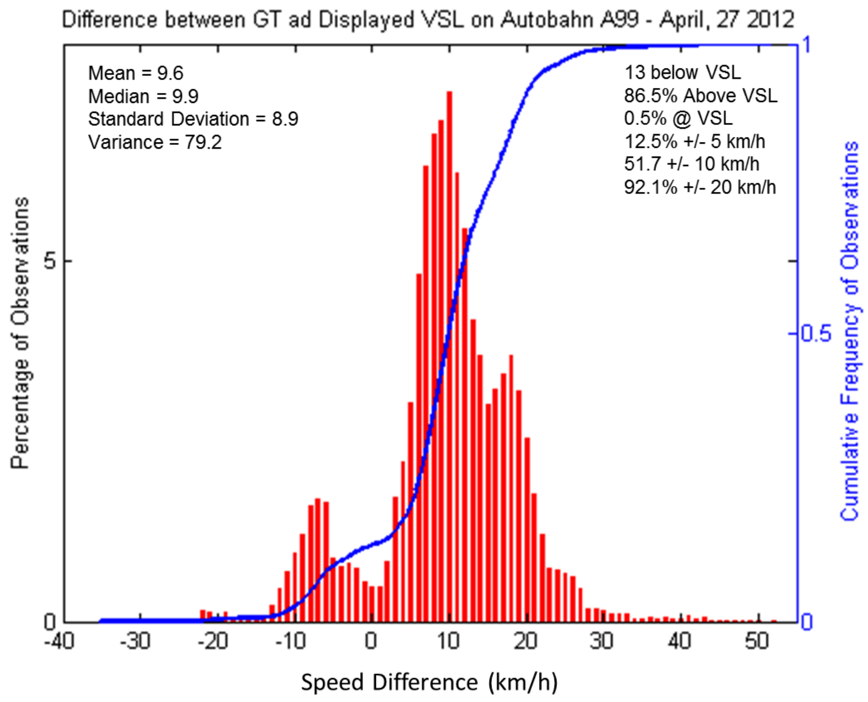
## B.1 Difference Histogram for VSL



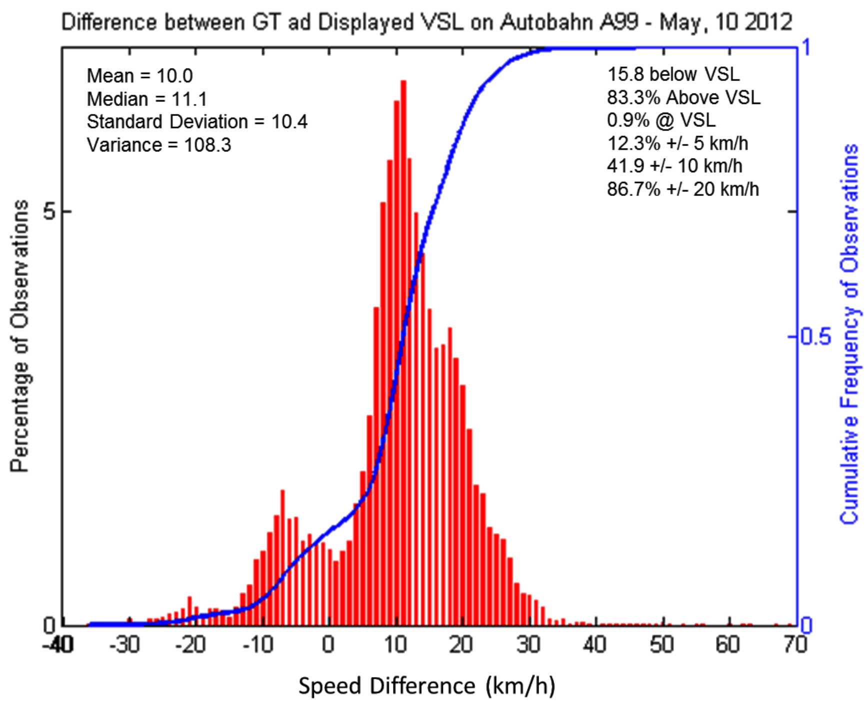

April, 01 2012



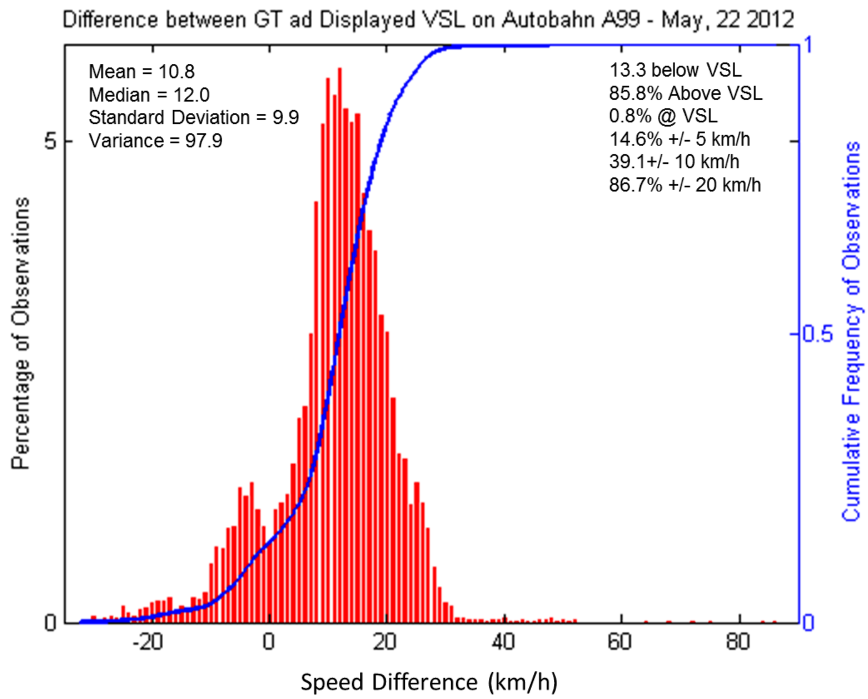

April, 19 2012



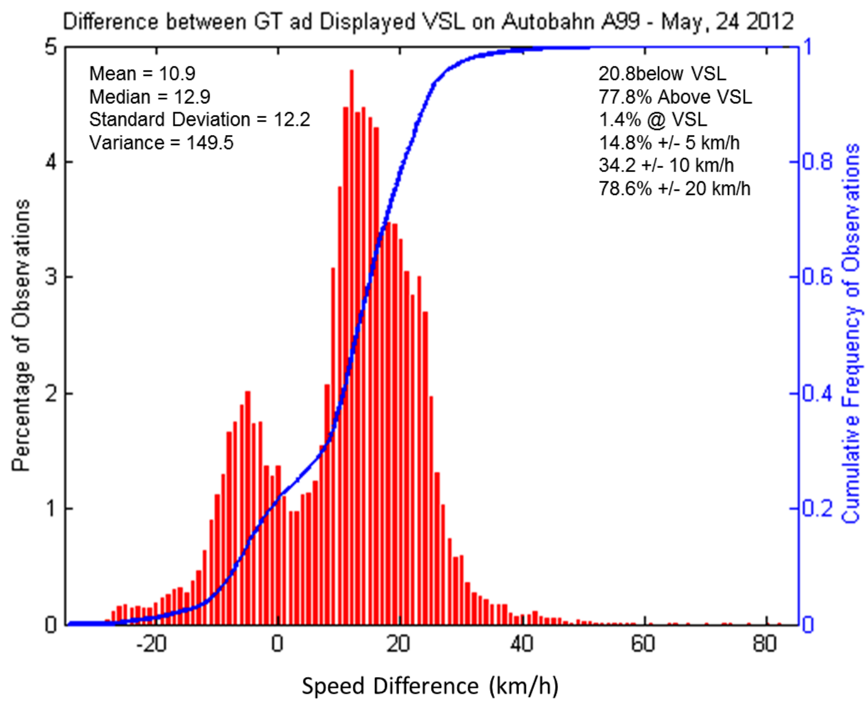

April, 27 2012



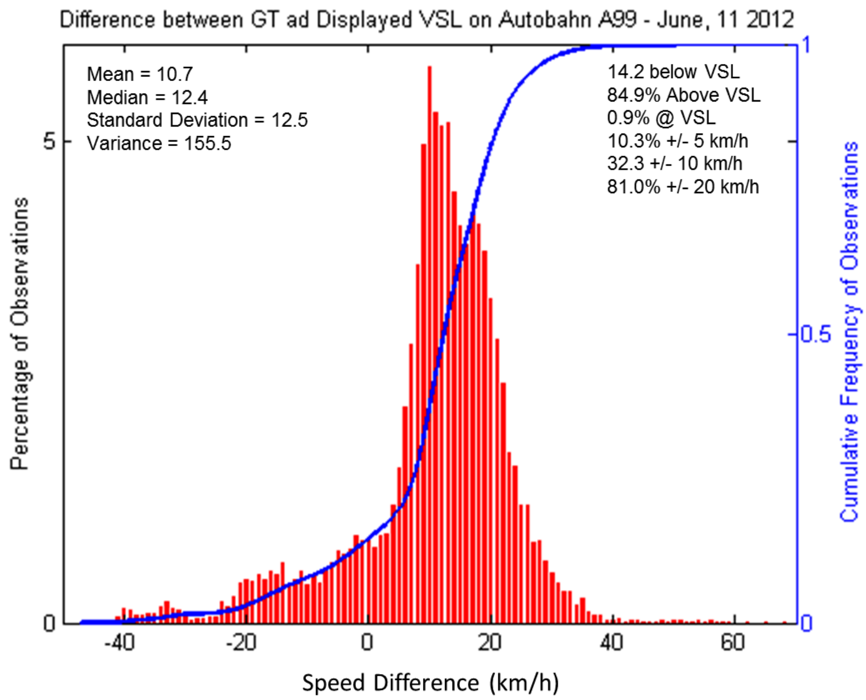

May, 10 2012



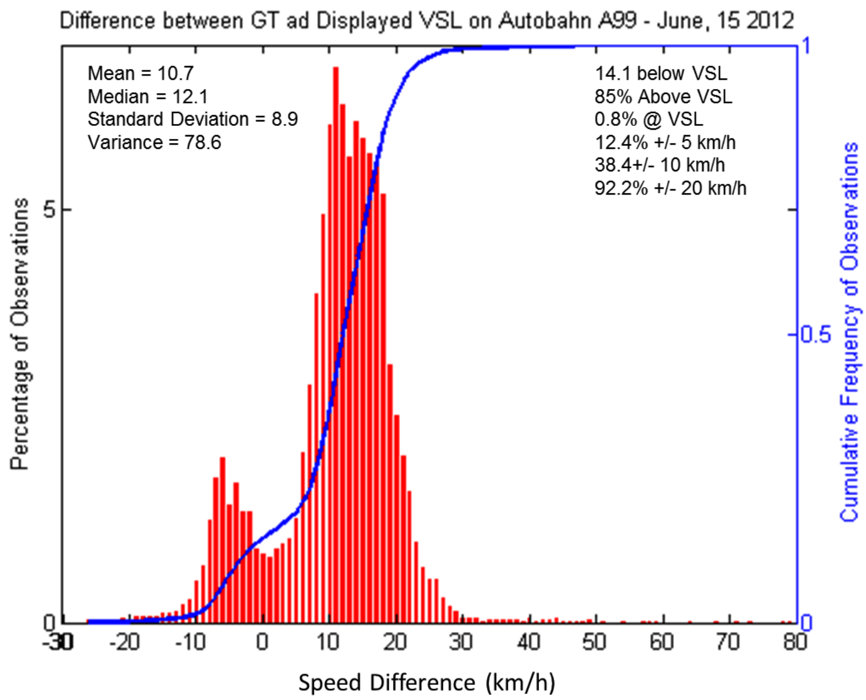

May, 22 2012



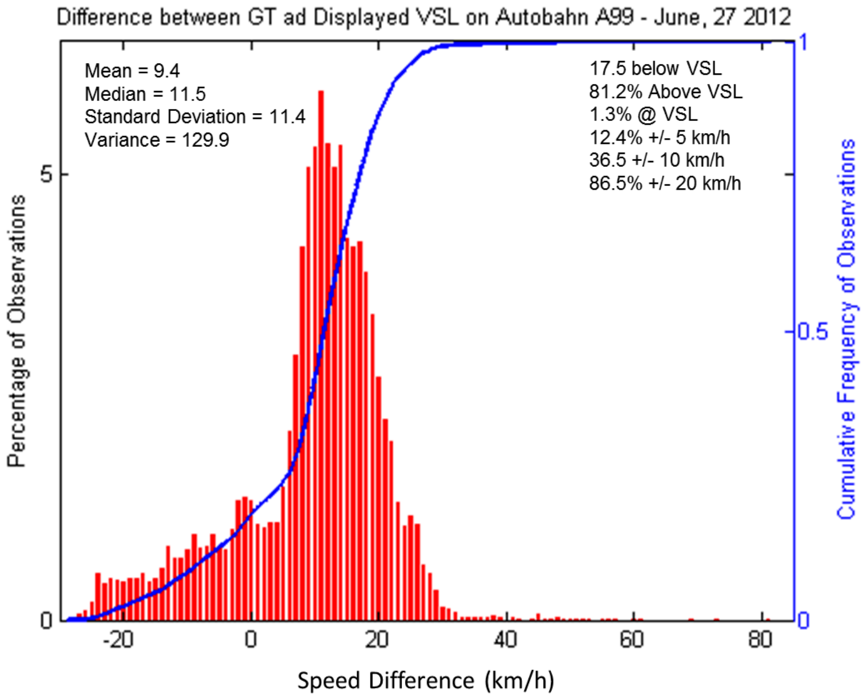

May, 24 2012



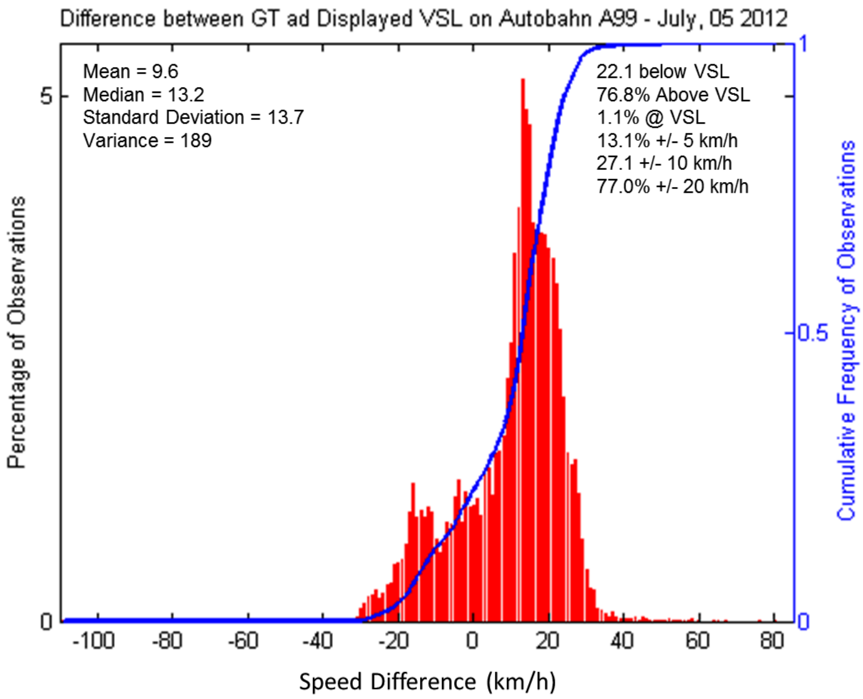

June, 11 2012



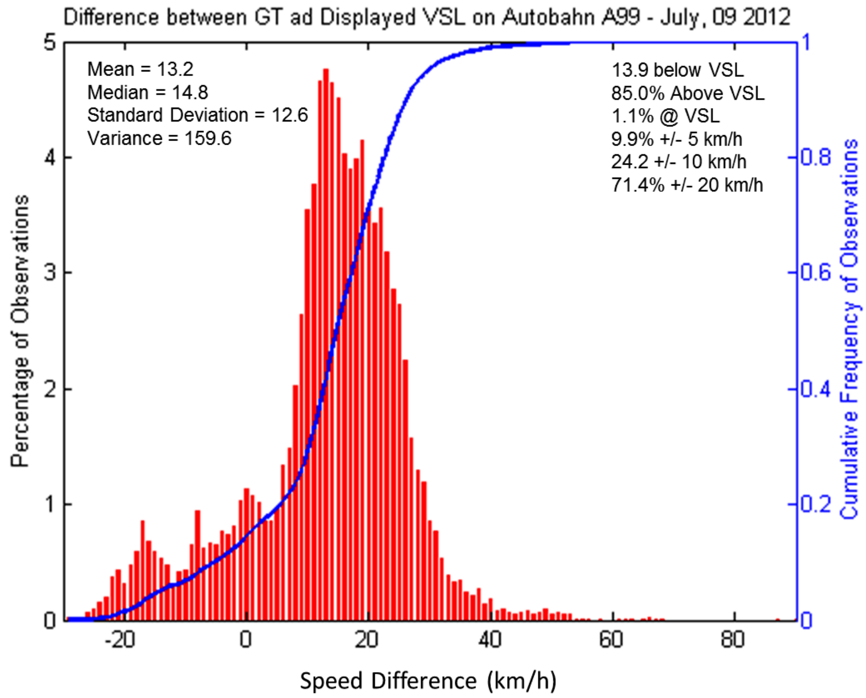

June, 15 2012



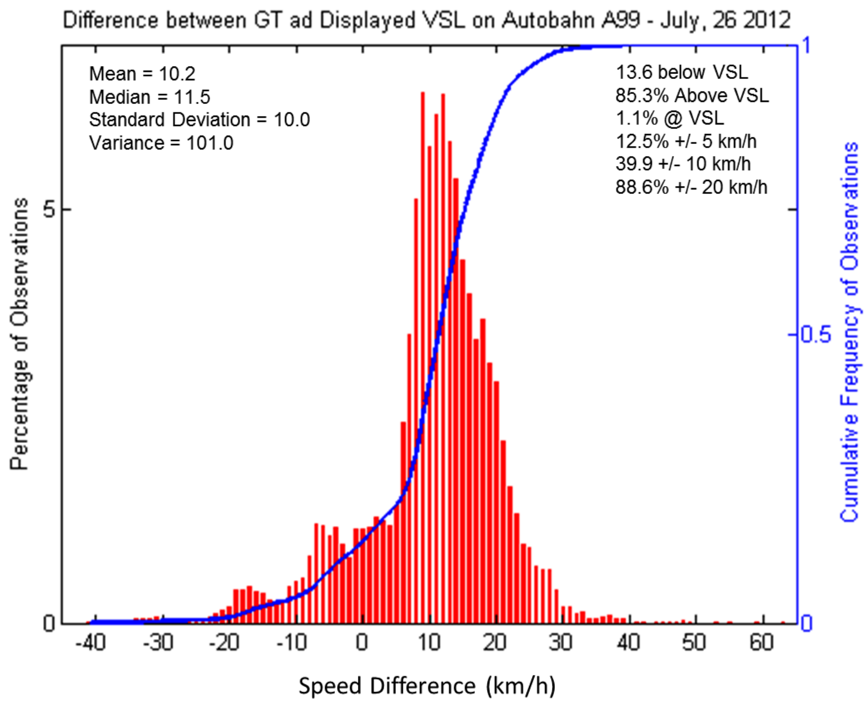

June, 27 2012




July, 05 2012

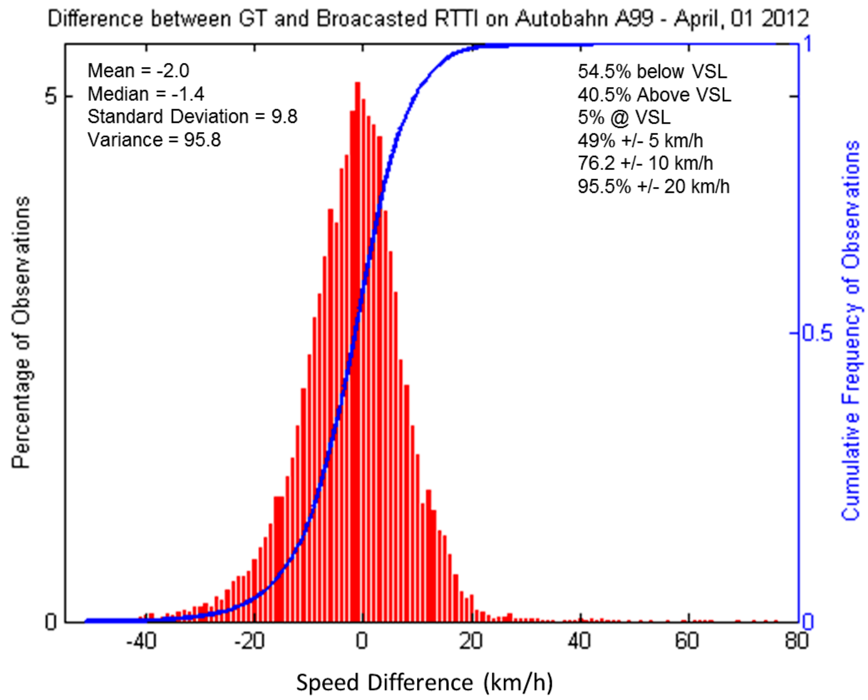



July, 09 2012

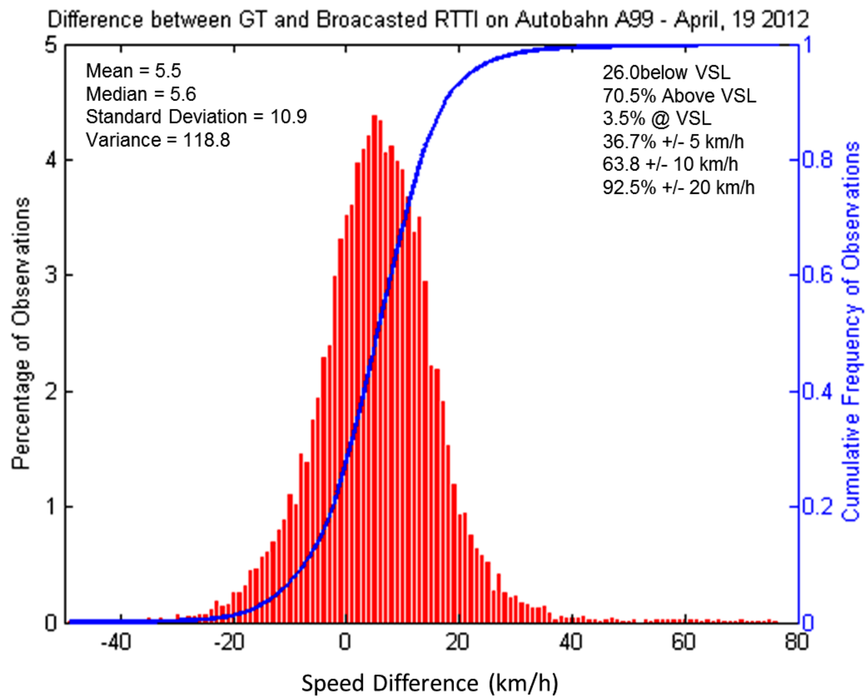



July, 26 2012

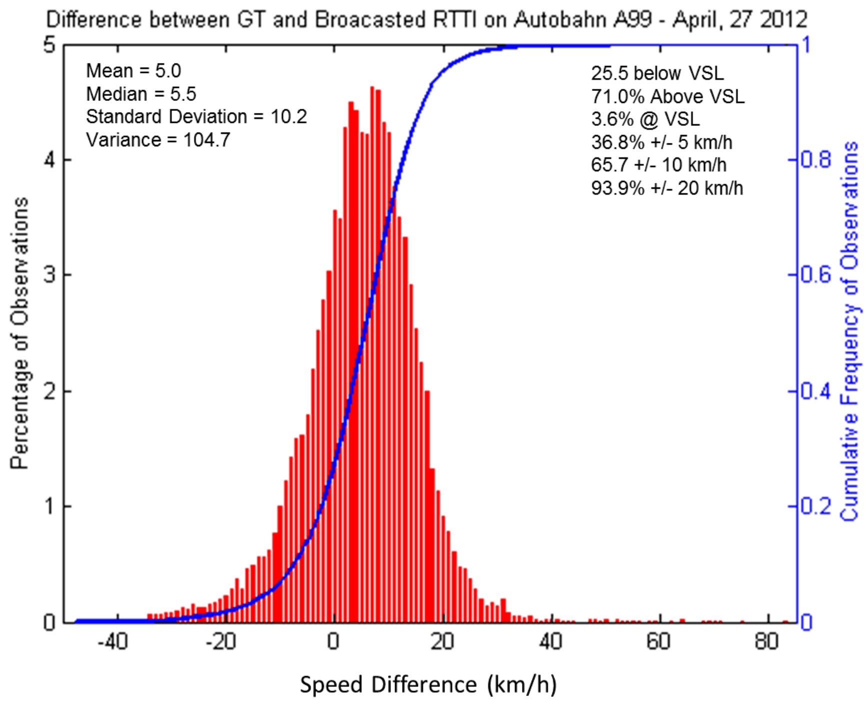
## B.2 Difference Histogram for RTTI



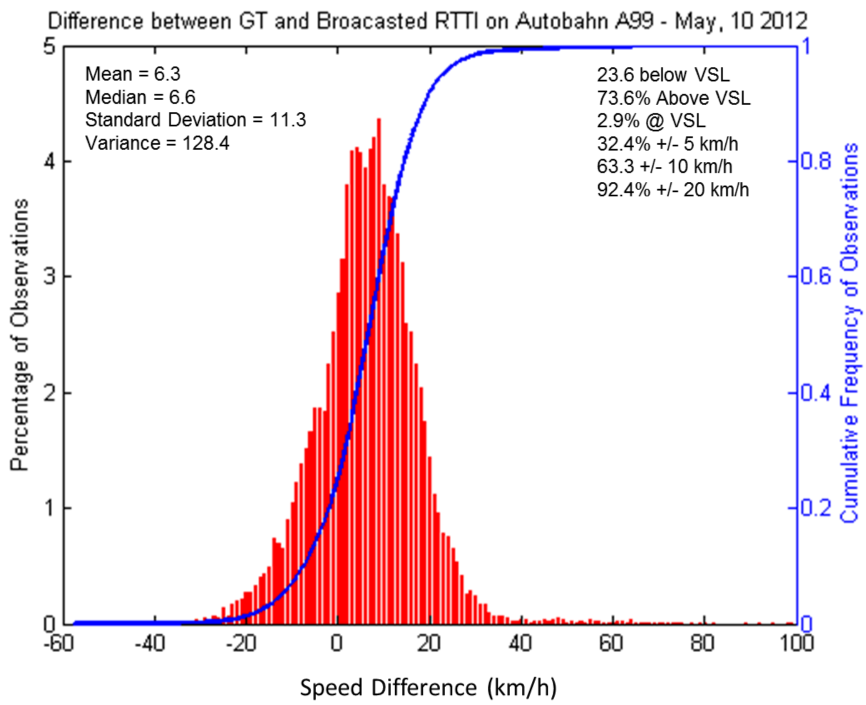

April, 01 2012



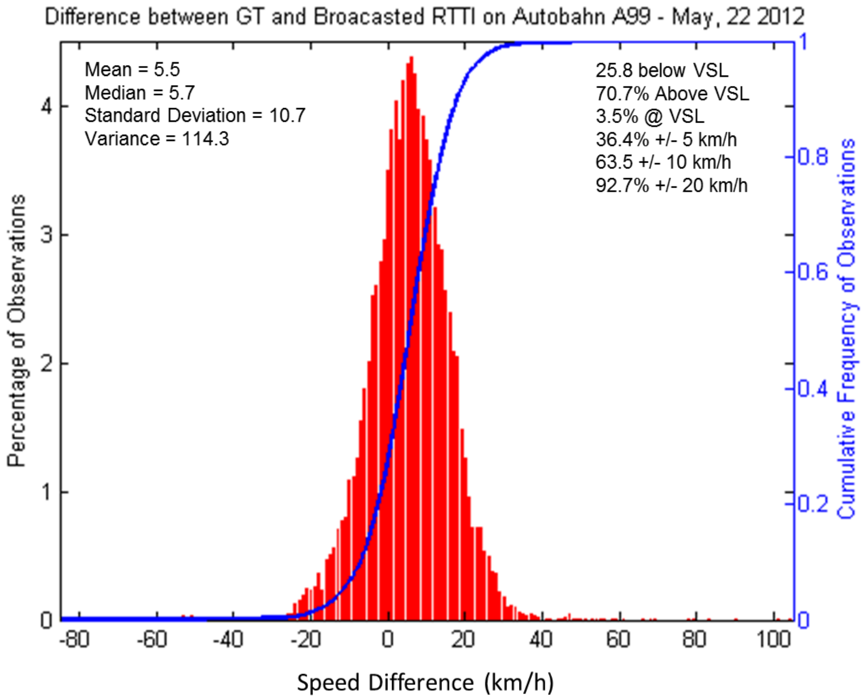

April, 19 2012



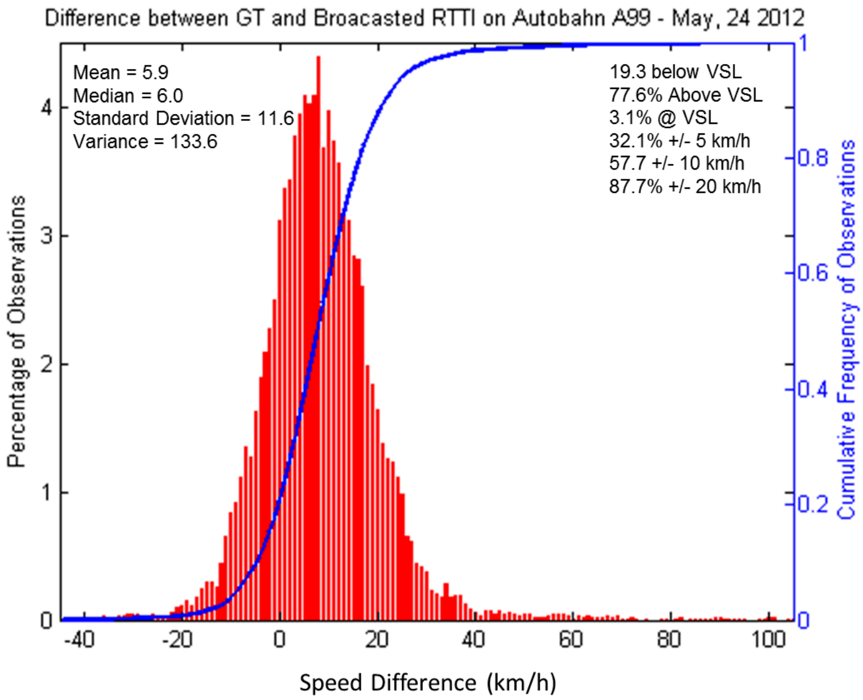

April, 27 2012



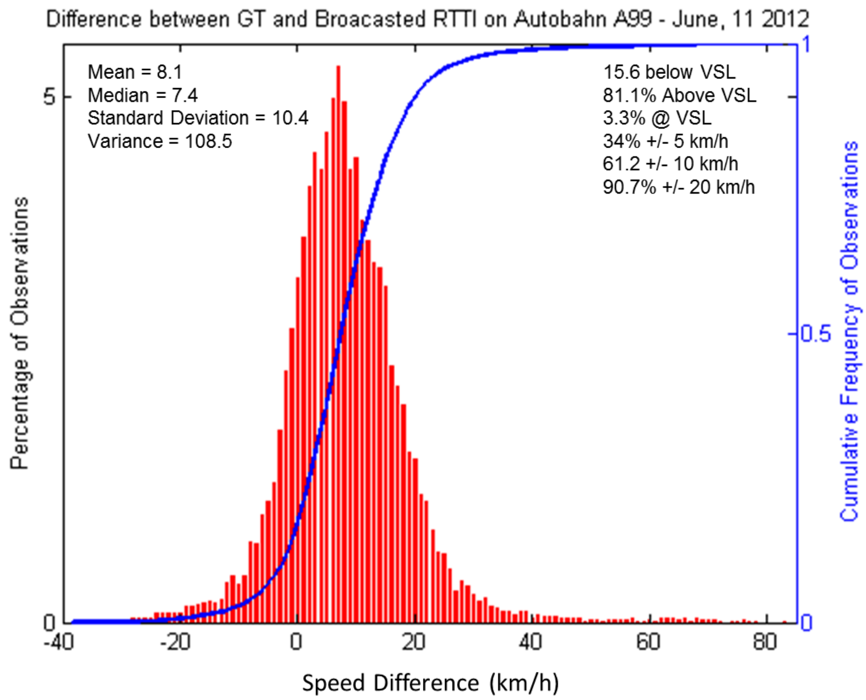

May, 10 2012



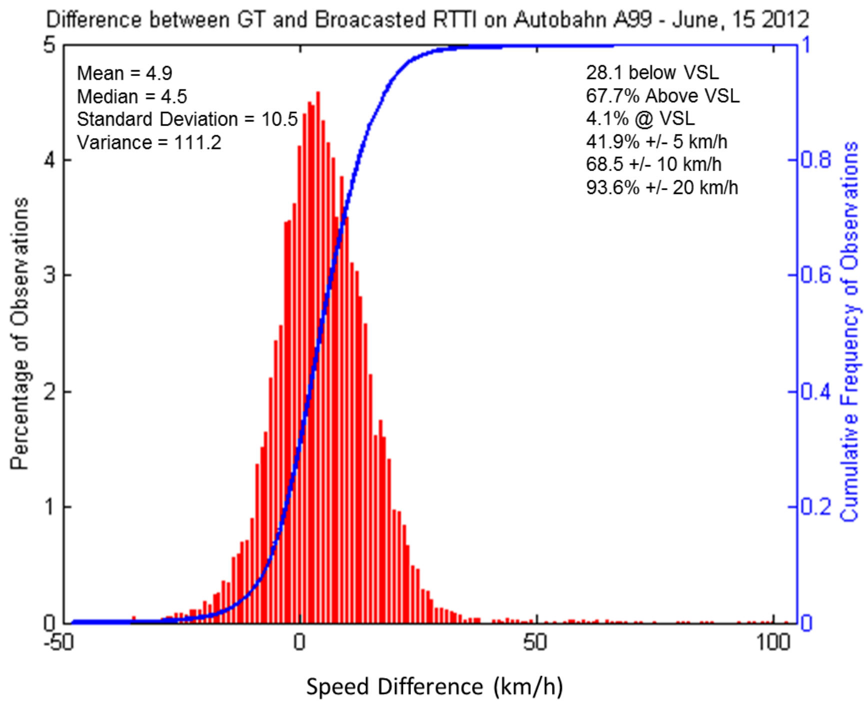

May, 22 2012



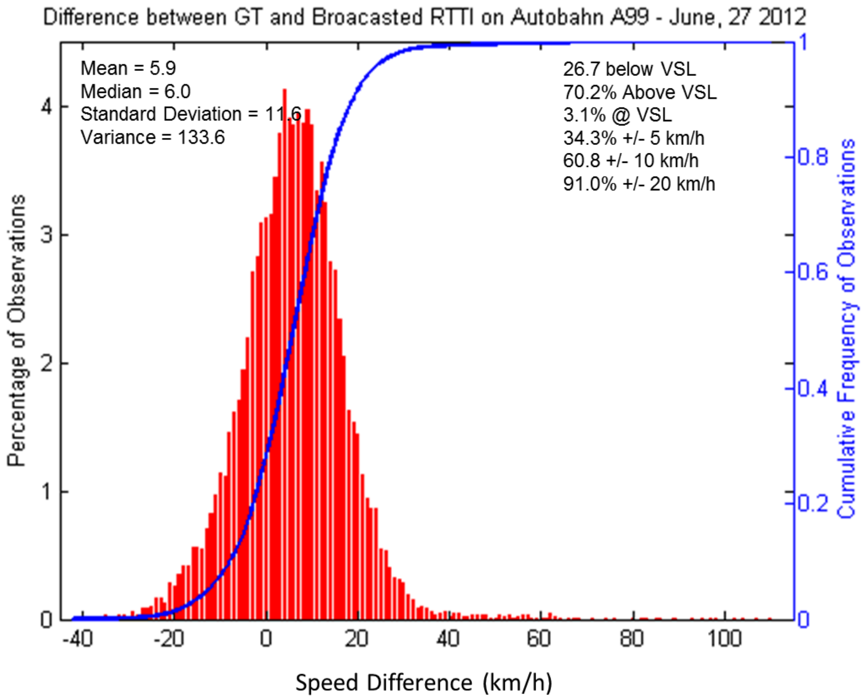

May, 24 2012



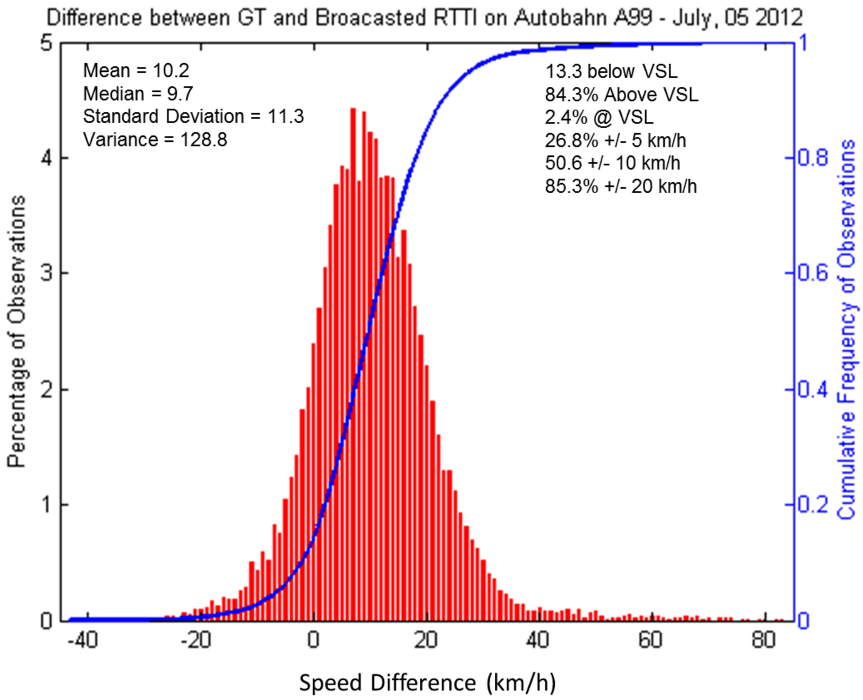

June, 11 2012



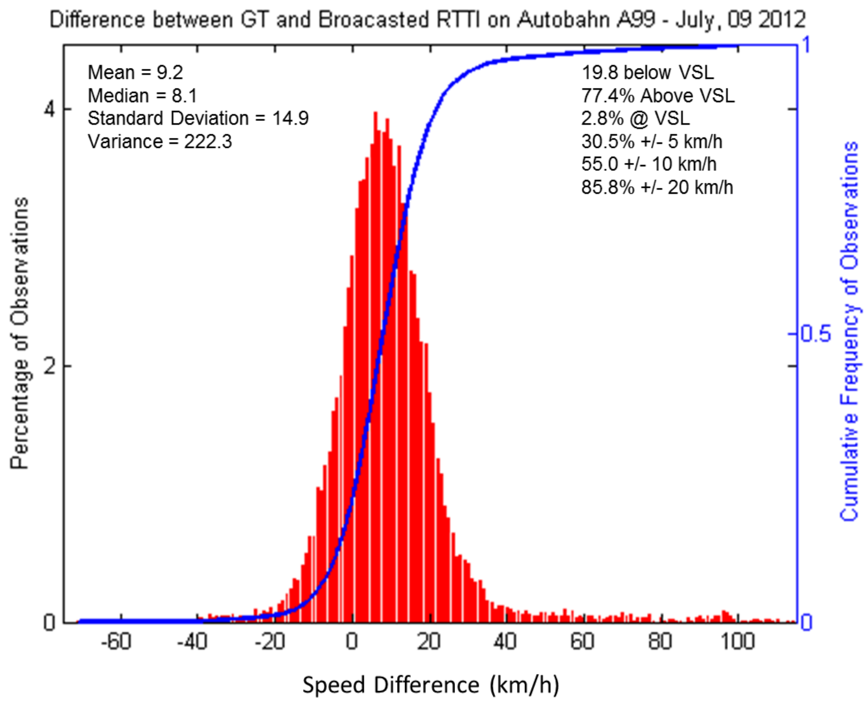

June, 15 2012



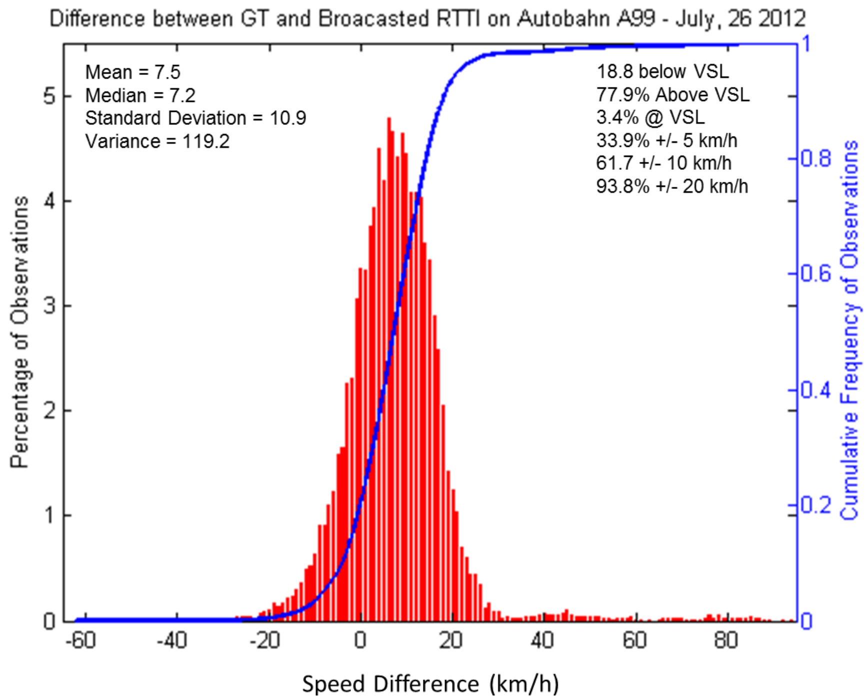

June, 27 2012




July, 05 2012




July, 09 2012




July, 26 2012

# Appendix C

# QKZ Values for Different Speed Thresholds and Performance on the Quality Scale

## C.1 Results of VSL Performance

Sensitivity of Different Speeds Thresholds on QKZ Indexes - VSL

| | **40 km/h** | | | **50 km/h** | | | **60 km/h** | | | **70 km/h** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* |
| 1-Apr-12 | 100.0 | 100.0 | F | 58.2 | 59.7 | D | 71.3 | 21.9 | B | 65.3 | 7.4 | B |
| 19-Apr-12 | 57.0 | 81.3 | D | 47.8 | 69.3 | E | 68.1 | 53.8 | C | 61.1 | 41.7 | C |
| 27-Apr-12 | 36.0 | 78.8 | E | 38.6 | 43.8 | D | 90.0 | 26.0 | B | 82.9 | 10.7 | A |
| 10-May-12 | 26.2 | 97.0 | F | 58.2 | 67.9 | D | 81.9 | 40.3 | B | 75.0 | 25.9 | B |
| 22-May-12 | 57.1 | 71.7 | D | 67.0 | 40.3 | C | 79.1 | 30.2 | B | 66.4 | 15.9 | B |
| 24-May-12 | 65.2 | 39.8 | C | 60.0 | 19.9 | C | 86.9 | 22.0 | B | 77.0 | 12.3 | B |
| 11-Jun-12 | 31.3 | 97.1 | F | 36.0 | 68.0 | E | 88.0 | 54.6 | C | 74.8 | 44.9 | C |
| 15-Jun-12 | 9.4 | 92.2 | F | 16.3 | 79.8 | F | 32.7 | 69.6 | E | 29.9 | 65.1 | E |
| 27-Jun-12 | 57.9 | 48.7 | D | 49.9 | 30.3 | C | 84.7 | 10.8 | A | 76.2 | 4.5 | A |
| 5-Jul-12 | 51.8 | 83.9 | E | 41.5 | 53.0 | D | 74.9 | 64.4 | C | 65.3 | 59.3 | D |
| 9-Jul-12 | 79.6 | 14.2 | B | 73.7 | 9.8 | B | 87.4 | 6.0 | A | 78.4 | 1.9 | A |
| 26-Jul-12 | 54.8 | 47.0 | D | 55.9 | 26.5 | C | 92.4 | 7.7 | A | 83.6 | 3.3 | A |

Sensitivity of Different Speeds Thresholds on QKZ Indexes - VSL *Continued*

| | 80 km/h | | | 90 km/h | | | 100 km/h | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* |
| 1-Apr-12 | 64.5 | 22.7 | B | 56.0 | 18.0 | C | 63.0 | 16.6 | B |
| 19-Apr-12 | 84.8 | 56.6 | C | 68.9 | 30.4 | C | 31.4 | 33.6 | D |
| 27-Apr-12 | 87.9 | 34.1 | B | 72.9 | 13.5 | B | 36.7 | 58.0 | E |
| 10-May-12 | 92.2 | 43.5 | B | 81.2 | 21.2 | B | 39.7 | 42.4 | D |
| 22-May-12 | 86.4 | 62.7 | C | 69.1 | 36.6 | C | 28.4 | 42.7 | D |
| 24-May-12 | 88.6 | 64.3 | C | 85.4 | 18.5 | B | 53.5 | 22.6 | C |
| 11-Jun-12 | 88.8 | 72.0 | F | 74.3 | 53.4 | C | 53.1 | 20.2 | C |
| 15-Jun-12 | 41.6 | 90.8 | E | 56.8 | 71.6 | D | 40.6 | 58.7 | D |
| 27-Jun-12 | 89.7 | 76.1 | F | 76.9 | 36.1 | C | 49.6 | 15.2 | C |
| 5-Jul-12 | 79.0 | 83.8 | F | 72.6 | 49.0 | C | 55.8 | 14.4 | C |
| 9-Jul-12 | 89.5 | 37.1 | B | 74.8 | 24.8 | B | 55.1 | 11.8 | B |
| 26-Jul-12 | 88.8 | 44.9 | B | 72.3 | 31.8 | C | 59.3 | 41.7 | C |

## C.2 Results of RTTI Performance

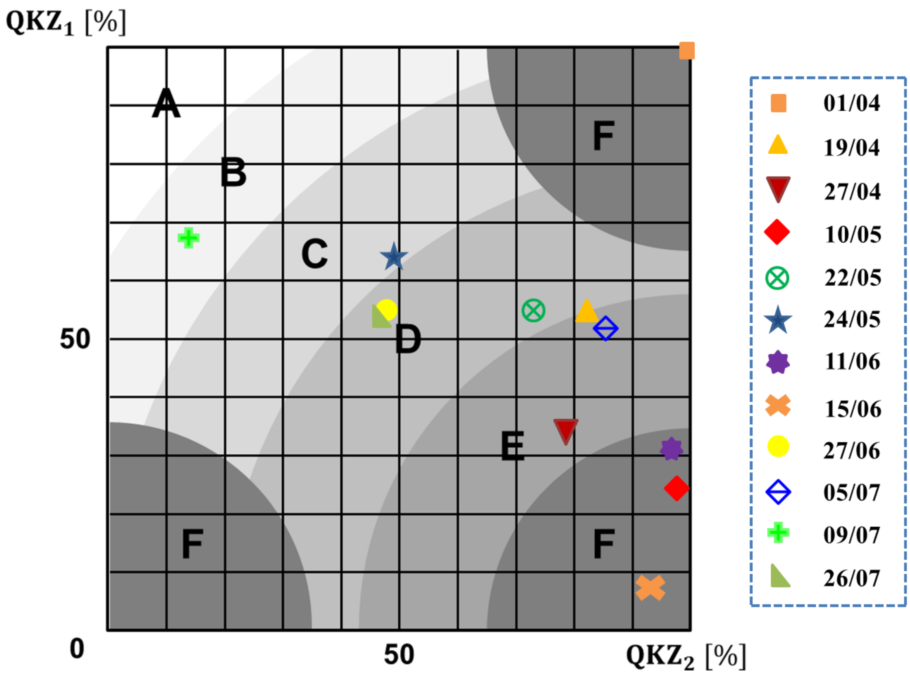
Sensitivity of Different Speeds Thresholds on QKZ Indexes - RTTI

| | **40 km/h** | | | **50 km/h** | | | **60 km/h** | | | **70 km/h** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* |
| 1-Apr-12 | 100.0 | 100.0 | F | 40.4 | 51.8 | D | 32.0 | 36.3 | D | 29.5 | 36.4 | D |
| 19-Apr-12 | 0.0 | 0.0 | F | 0.0 | 0.0 | F | 3.9 | 0.0 | F | 17.0 | 0.0 | F |
| 27-Apr-12 | 4.1 | 57.1 | E | 24.0 | 16.3 | F | 33.3 | 37.7 | D | 46.7 | 25.9 | C |
| 10-May-12 | 0.0 | 0.0 | F | 1.8 | 92.2 | F | 16.2 | 31.0 | F | 25.9 | 17.1 | F |
| 22-May-12 | 38.9 | 56.3 | D | 21.1 | 58.9 | E | 14.4 | 47.5 | E | 20.3 | 43.9 | D |
| 24-May-12 | 24.1 | 31.0 | D | 11.5 | 34.5 | D | 21.1 | 17.5 | F | 28.3 | 18.6 | F |
| 11-Jun-12 | 0.0 | 0.0 | F | 0.8 | 0.0 | F | 5.3 | 12.3 | F | 5.2 | 20.1 | F |
| 15-Jun-12 | 0.0 | 100.0 | F | 7.5 | 0.0 | F | 11.2 | 0.0 | F | 20.1 | 0.0 | F |
| 27-Jun-12 | 1.2 | 0.0 | F | 3.8 | 0.0 | F | 11.0 | 2.9 | F | 15.2 | 7.6 | F |
| 5-Jul-12 | 0.0 | 0.0 | F | 0.0 | 0.0 | F | 0.0 | 100.0 | F | 3.2 | 60.7 | E |
| 9-Jul-12 | 32.3 | 1.6 | F | 30.0 | 2.3 | F | 37.4 | 2.2 | F | 47.2 | 2.2 | B |
| 26-Jul-12 | 3.2 | 0.0 | F | 16.4 | 0.0 | F | 10.8 | 0.8 | F | 10.8 | 0.6 | F |

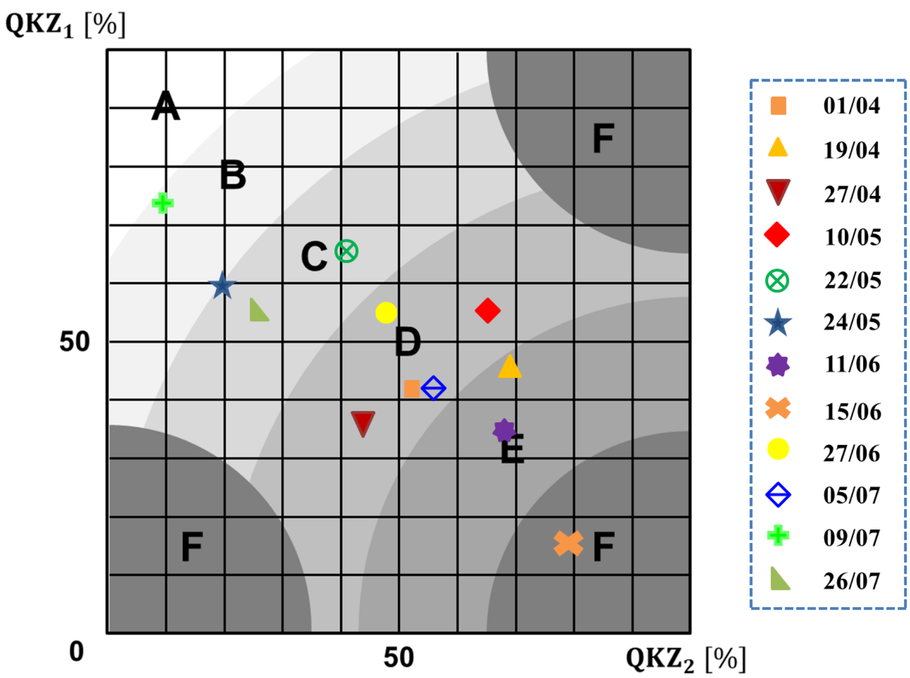
Sensitivity of Different Speeds Thresholds on QKZ Indexes - RTTI *Continued*

| | **80 km/h** | | | **90 km/h** | | | **100 km/h** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* | $QKZ_1$ | $QKZ_2$ | *Grade* |
| 1-Apr-12 | 31.6 | 32.8 | D | 34.5 | 48.0 | D | 22.2 | 83.9 | F |
| 19-Apr-12 | 34.6 | 6.1 | F | 28.9 | 49.6 | D | 25.3 | 36.3 | D |
| 27-Apr-12 | 59.2 | 13.9 | B | 48.2 | 20.2 | C | 22.7 | 48.7 | D |
| 10-May-12 | 37.1 | 5.6 | B | 43.3 | 10.0 | C | 26.1 | 26.4 | D |
| 22-May-12 | 44.6 | 30.4 | C | 26.3 | 47.1 | D | 14.6 | 46.8 | E |
| 24-May-12 | 34.6 | 11.2 | C | 32.8 | 13.7 | F | 32.6 | 17.7 | C |
| 11-Jun-12 | 5.5 | 37.2 | D | 8.3 | 72.8 | F | 16.0 | 34.6 | F |
| 15-Jun-12 | 51.4 | 13.3 | C | 35.8 | 23.3 | C | 22.8 | 39.0 | D |
| 27-Jun-12 | 23.2 | 21.0 | F | 16.9 | 37.5 | D | 20.9 | 38.3 | D |
| 5-Jul-12 | 11.6 | 49.6 | E | 12.8 | 39.0 | D | 20.2 | 16.1 | F |
| 9-Jul-12 | 59.0 | 3.9 | B | 49.3 | 11.9 | C | 36.7 | 15.8 | C |
| 26-Jul-12 | 20.2 | 0.3 | F | 23.6 | 20.6 | F | 18.3 | 50.7 | E |

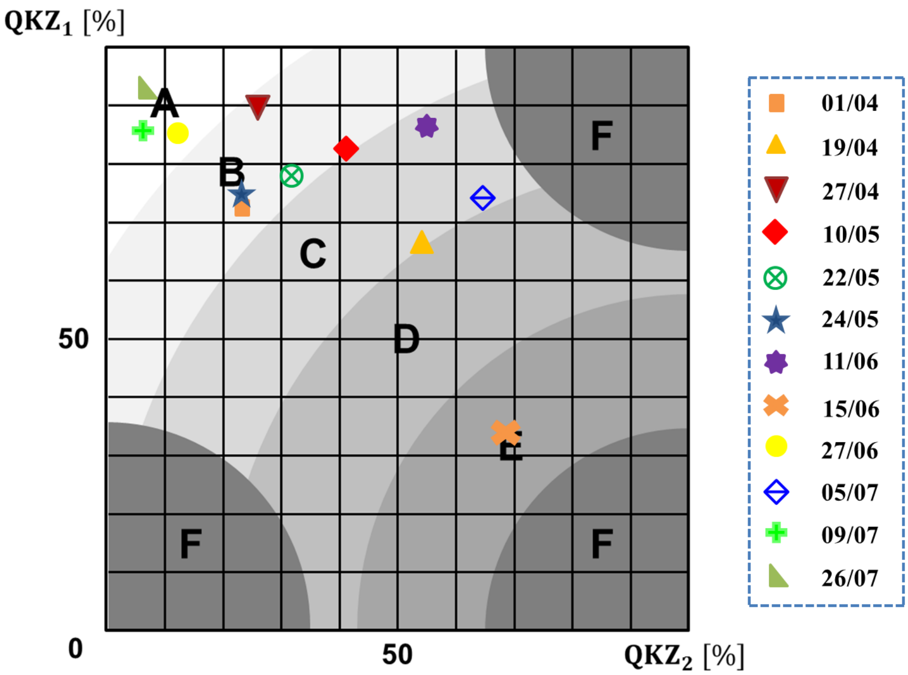
## C.3 VSL Performance on the Quality Scale



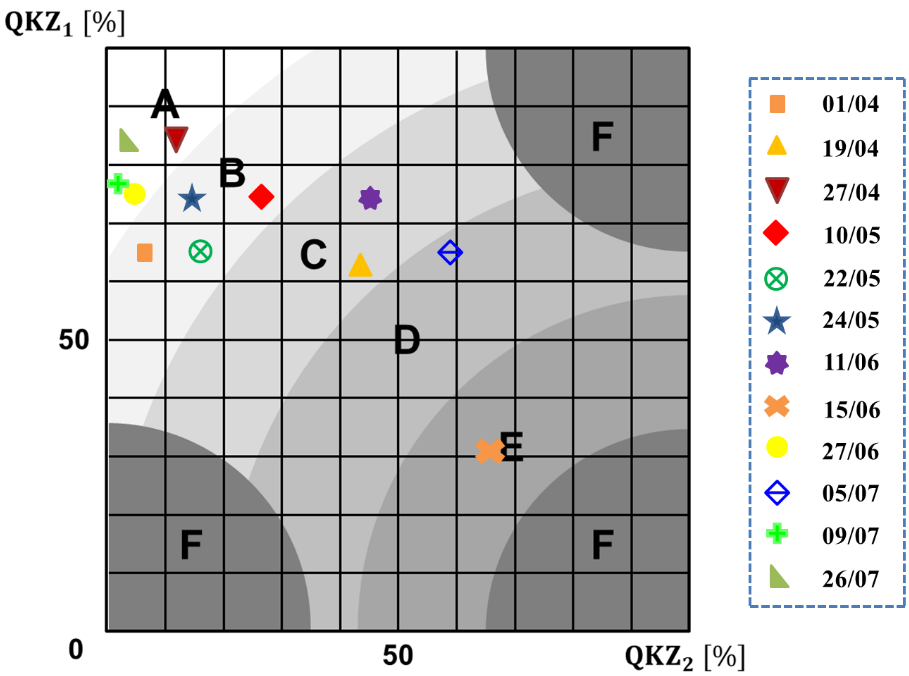

Speed Threshold = 40 km/h



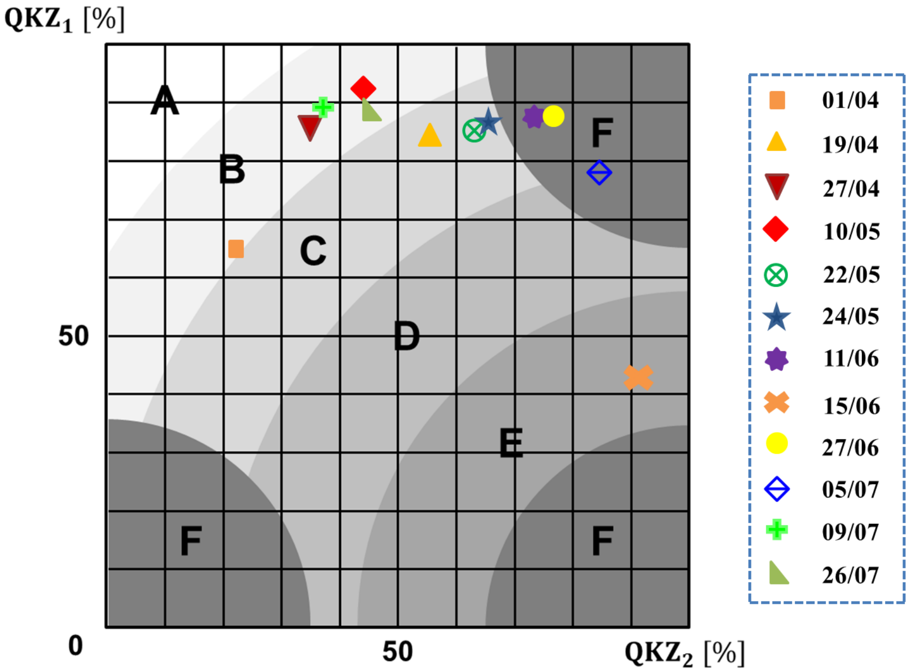

Speed Threshold = 50 km/h



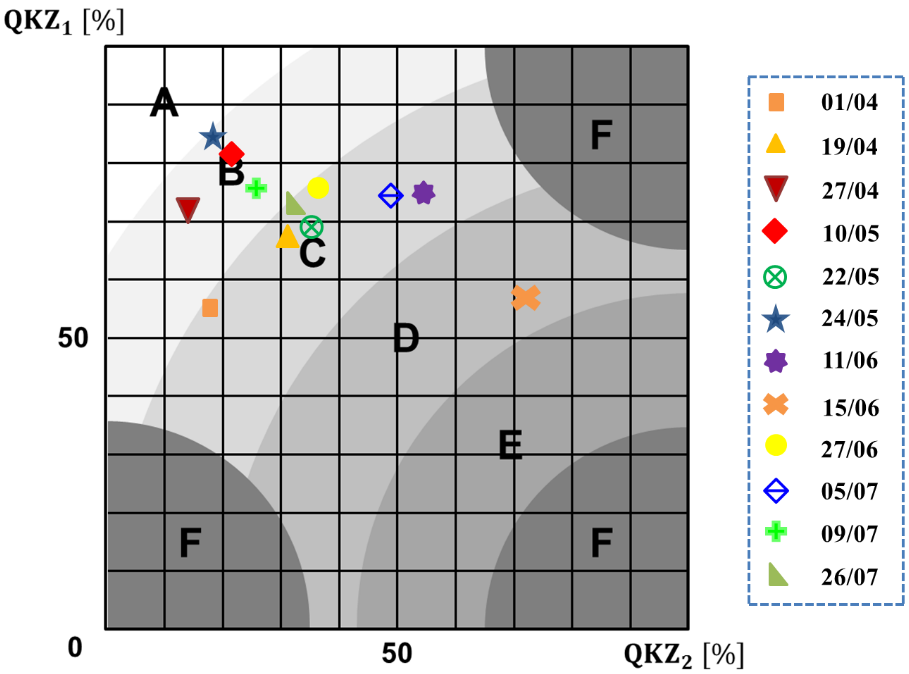

Speed Threshold = 60 km/h



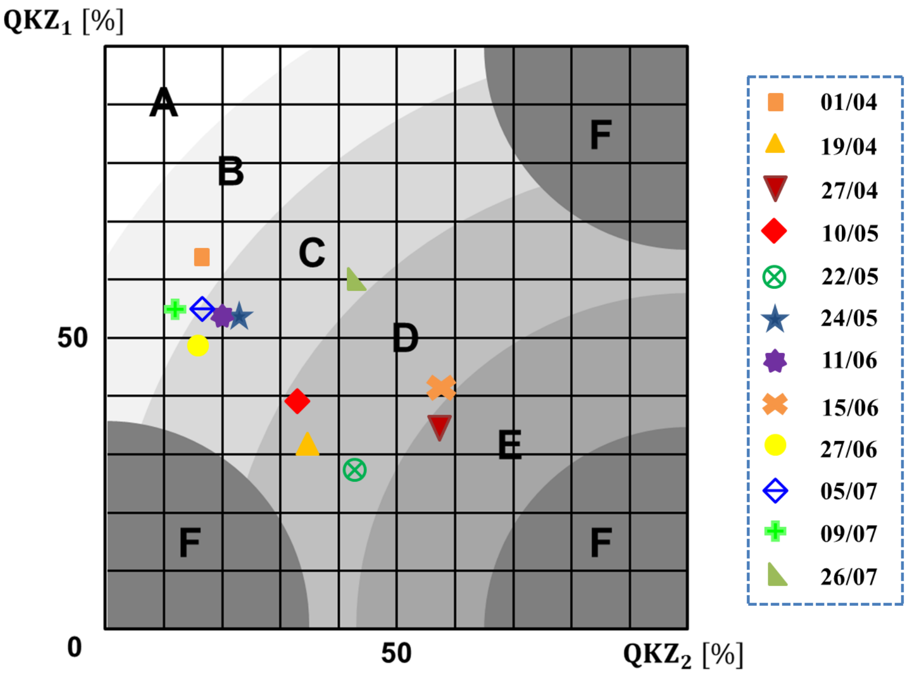

Speed Threshold = 70 km/h




Speed Threshold = 80 km/h

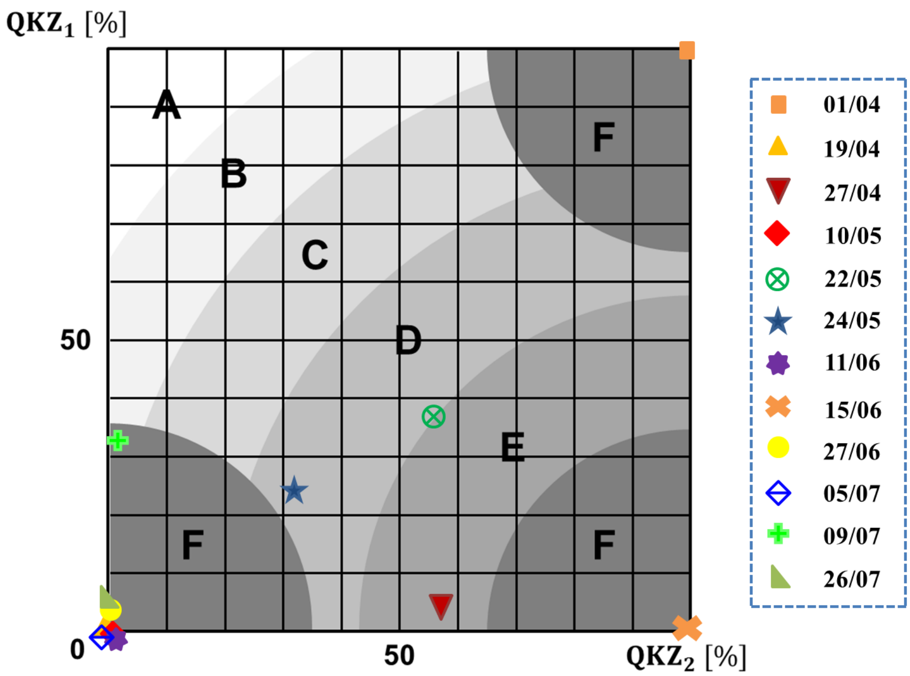



Speed Threshold = 90 km/h

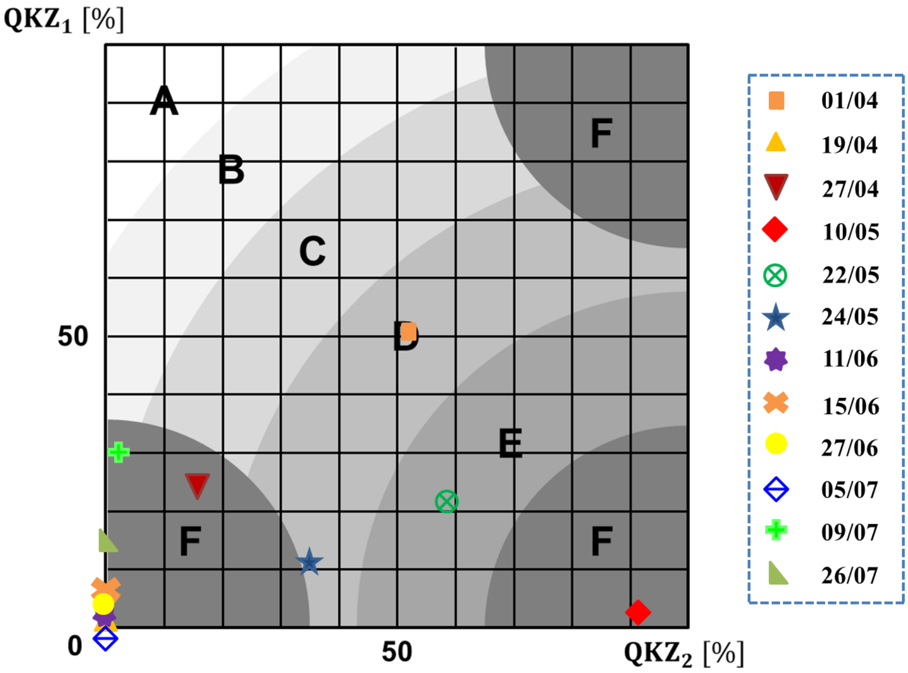



Speed Threshold = 100 km/h

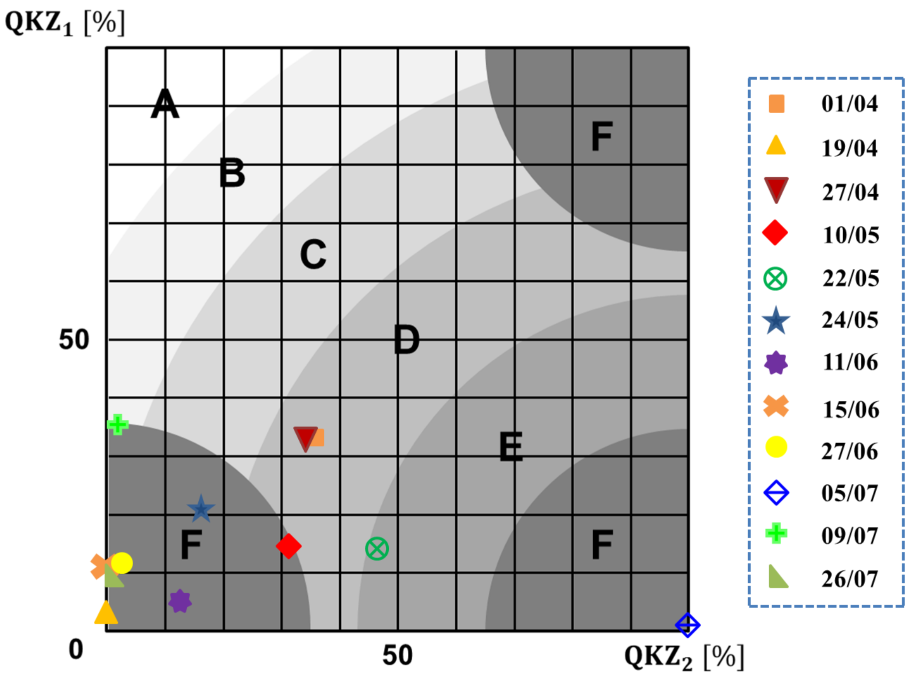
## C.4 RTTI Performance on the Quality Scale



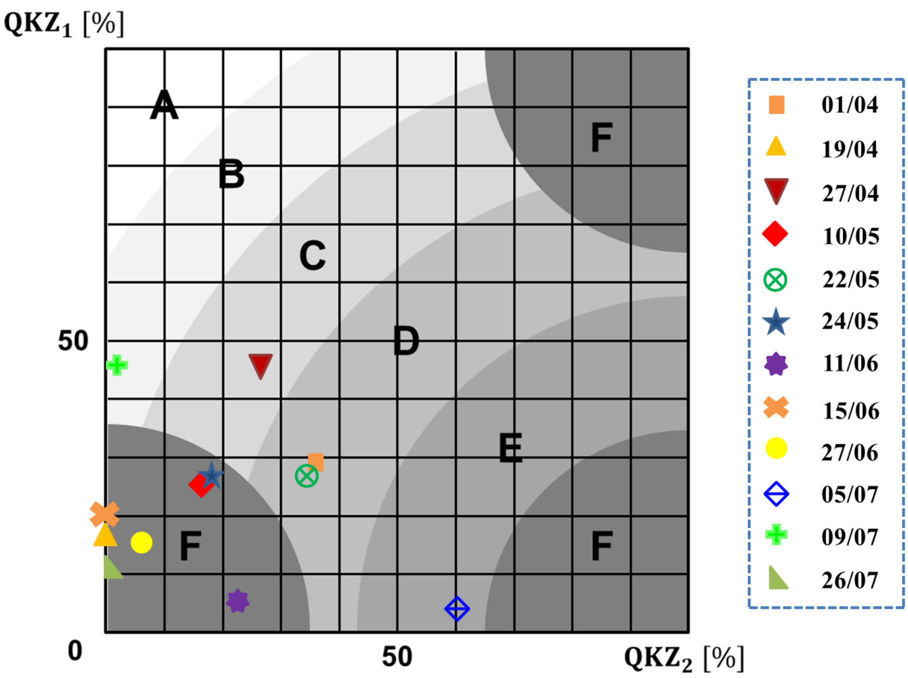

Speed Threshold = 40 km/h



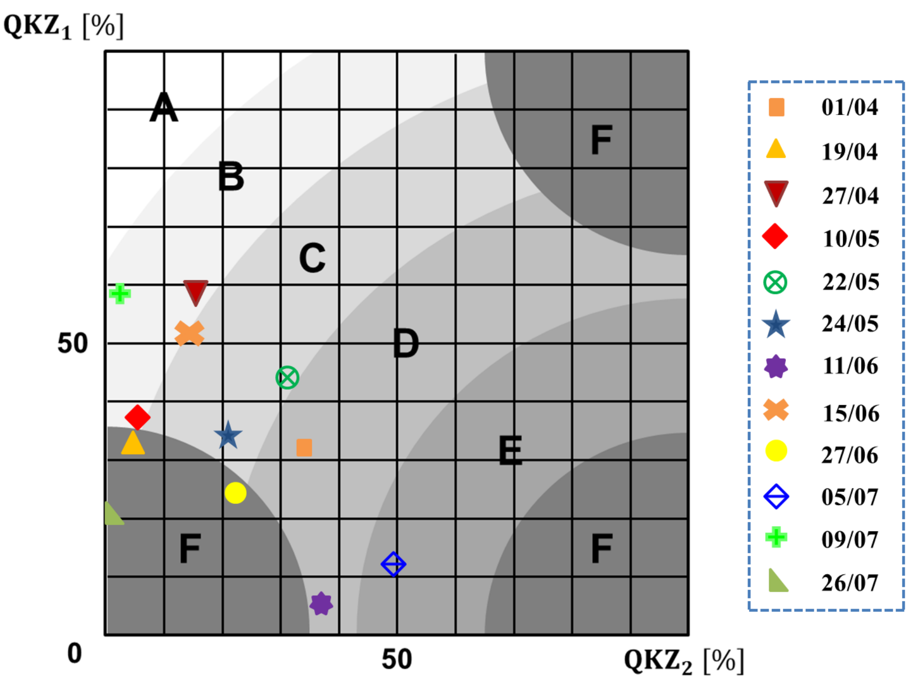

Speed Threshold = 50 km/h



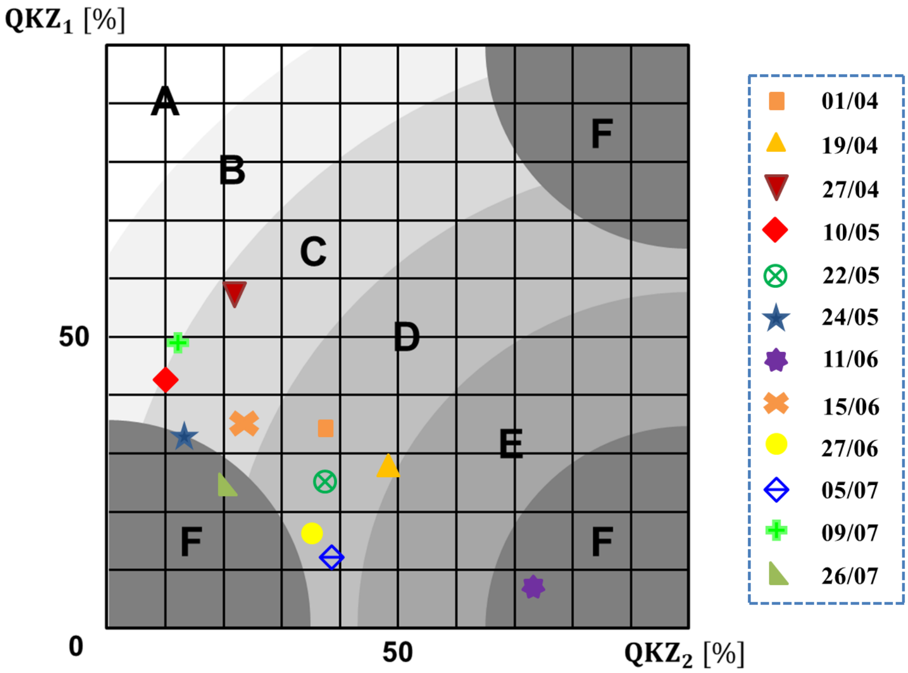

Speed Threshold = 60 km/h



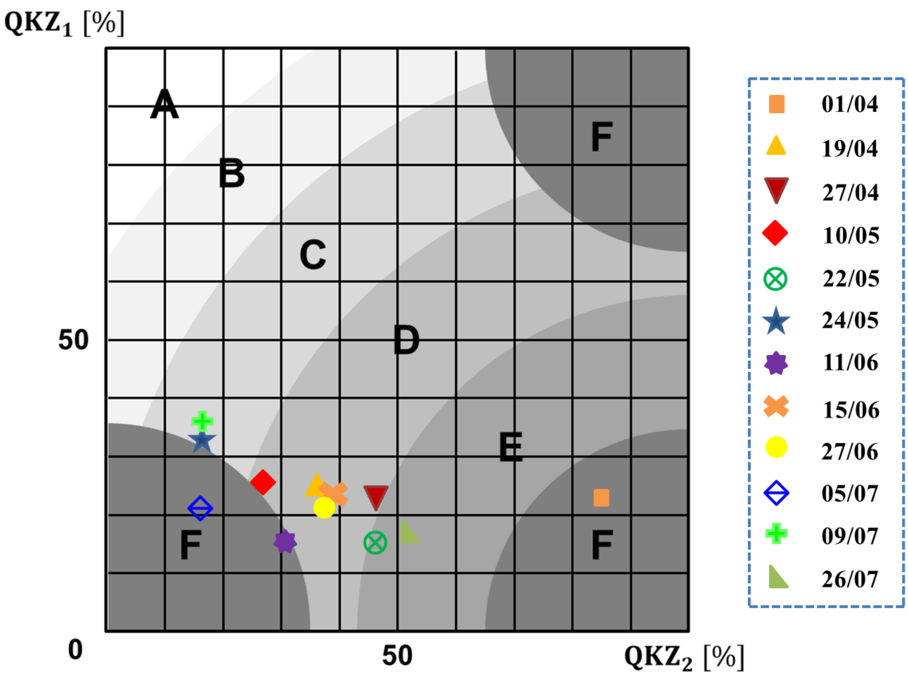

Speed Threshold = 70 km/h




Speed Threshold = 80 km/h




Speed Threshold = 90 km/h




Speed Threshold = 100 km/h

# Index