Czech Technical University in Prague

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Evaluation of the breakdowns predicting algorithm using a probability approach for traffic management application

(Master thesis)

2012

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Evaluation, Variable speed limits, Traffic breakdown, Capacity, Algorithm, Quality

Supervisors

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Abstract

The main purpose of thesis meets two fundamental needs. First, it is desired to research the variable speed limits algorithm's quality based on the real bulk data acquired at Austrian highways. Naturally, it requires providing the clearly understandable results, which among the others, reflecting the roadway stochastic capacity approach employment. Second, attention is devoted to the own proposed evaluation technique in matter of its further applicability. It appears that the proposed evaluation method, created as software mean, delivers a solid tool that has wide use for the speed reduction algorithms, from the control strategy development where the algorithm aims on the quality evaluation, to the overall performance assessment. Using the designed methods, some favourable results were revealed. Among the others, the AIX-ProB has ability to control the majority of congestions with minimum of the superfluous (false) critical interventions. The algorithm proved great preventive nature that is crucial for successfully operable variable speed limits system. Additionally, it delivered better results in the all compared criteria than the currently used strategy at Austrian and German freeways.

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Abbreviations

ATM	Active Traffic Management
DR	Detection Rate
FAR	False-alarm Rate
ITS	Intelligent Transportation Systems
STSF	Space-Time Speed Field
SW	Software
VSL	Variable Speed Limits

1 INTRODUCTION

The world has recently experienced massive increase of individual and freight road transport; this trend is continuing with the growing population, the society richness and the world globalization. Naturally, this progressive development has raised several drawbacks. The two probably most discussed topics, regarding road transport nowadays are the negative environmental impact and the safety risks. In both of these areas, society achieved the significant results, for example the electric vehicles (which are currently deployed over the big Europe cities) and the vehicle active safety systems (intelligent active safety systems, for example adaptive cruise control). However, safe and environmentally convenient road transport has still an enormous challenge to face. It is a matter of transport sustainability and freedom of mobility. The random vehicle passengers, daily commuters or commercial vehicles (freight transport) are daily "freezing" in the congestions. This situation is primarily connected to extensive massive resources (financial and time) losses; however the environmental and safety issues can be observed as well. The congestion phenomenon is not a trivial task to solve and requires a broad umbrella of solutions. As one of the possibility, the active traffic management (ATM) considering wide range of the sub-systems can be introduced in order to reduce congestion impact. Focusing on the European context, the ATM systems has already proved their importance, Mirshahi et al. (2007) for example stated that an increase in average throughput for congested periods of 3 – 7 % , an increase in overall capacity of 3 – 22% or a decrease in secondary incidents of 40 – 50 % were experienced. A typical representative of ATM in Europe is the variable speed limits (VSL) system that has recently achieved throughput increase by 3 – 5 % and collision reduction about 16 %, stated in Neudorff et al. (2006).

The thesis evaluates the VSL control algorithm proposed and designed in Schwietering (2010). In general, VSL algorithm aims on smoothing the traffic stream by determining the roadway capacity value. The traditional approach that has been employed over the past years is using the capacity as a deterministic value, utilizing the well-known traditional traffic fundamental three models. However, it has appeared that this definition reached its limitations. The researches, for example Minderhoud et al. (1997), Persaud et al. (1998), Brilon (2000), Okamura et al. (2000), Lorenz & Elefteriadou (2001), Brilon & Geistefeldt (2009) or Schwietering & Steinauer (2011), empirically proved that using the fundamental model and the capacity as deterministic value does not reliably delineate a current traffic conditions for which are the speed reduction set. As an alternative, the stochastic capacity concept is proposed. The stochastic approach determines roadway capacity by using so-called traffic breakdown alias transition from fluent traffic into the congested traffic conditions.

Having real bulk data, it is intended to evaluate the innovative traffic breakdown predicting algorithm. For this purpose, the author investigates and designs a three-dimensional, so-called Space-Time Speed Field STSF method that would report the algorithm's quality aspects. The method has been additionally re-transformed into a software program applicable on the enormous amount of data

1.1 Foundation of Structure

The thesis body is principally divided into the two main sections. The first section can be understood as a knowledge base for further evaluation. It consists of chapter 2, a literature review and chapter 3, researching traffic algorithm description. Additionally, chapter 2 consists of the three sub-chapters which are dealing with the theoretical background about traffic data (roadway capacity), then discussing the evaluation methods for traffic algorithms and the last sub-chapter outlines the current state of active traffic management tools.

The second main section of thesis' body is devoted to the practical research. It starts by the chapter 4 that presents the developed evaluation method designed. For each method, the method description includes motivation same as the impact of the method's results. Once the methodology is delivered, the thesis' core, a traffic breakdown predicting algorithm evaluation (chapter 5) is provided. This chapter shows results and subsequently putting them into the context of previous text. The message out of these results is then covered in the conclusion, chapter 6.

1.2 Motivation

The introduction's opening indicates the subject of matter and highlights the milestones of the research. Besides that some difficulties were outlined. As was stated before, the essential point is the algorithm evaluation regarding the quality. However, what exactly determines the algorithm's quality? What are the relevant measures? For example, if the algorithm delivers the speed reduction and no current conditions imply any "problem" in traffic; does it mean that the algorithm carried out an incorrect speed reduction? Note the preventive algorithm's nature and fact that it is intended to anticipate the breakdowns (rather than observe), then this speed reduction would be potentially favourable and definitely fulfills the needs of timely control.

And additionally, once a system of possible quality parameters is identified, a way how to scale and understand the results has to be found. In the other words, if the algorithm posts the speed reduction 3 minute before the anticipate incident, is that the most favorable solution? Or is it just an acceptable but the excellent control would be rather in a five advance?

The fundamental problem, for example discussed at Brilon & Geistefeldt (2009), is a definition of the traffic breakdown, or rather, a definition of congested and un-congested traffic conditions. If one would ask a daily commuter for his or her definition, an answer would probably reflect a time increment in commuter's daily travel time. Obviously, similar hypothesis is not applicable in transport engineering. However, which parameters and what values are represent congestions? For example, one can state a hypothesis that decrease of 8 km/h, from 64 km/h to 56 km/h measured between two one-minute intervals, is a traffic breakdown. Then, the speed drop from 74 km/h to 66km/h is a traffic breakdown as well? Is it further sufficient to use static definition, used by Bogenberger (2004), that all speeds below 50 km/h performs congestion traffic?

One straightforward approach how to evaluate the newly proposed algorithm would be to compare the results obtained by the old, currently deployed system and in contrast, put next to them the values received from the new algorithm. Such a comparison would probably provide unambiguous interpretation of the new algorithm effect. However, this data (observed velocity from the real environment) are not available. Besides that, this thesis has higher ambitious than just provide a comparison. An objective is to develop a tool usable for the bulk data that would clearly indicate the overall algorithm performance same as evaluate the relevant quality measures.

2 LITERATURE OVERVIEW

The literature overview chapter body is divided into the three parts. The first part researches traffic data, specifically roadway capacity. The special attention is devoted to the difference between the stochastic and deterministic interpretation. The author then makes a step towards the evaluation methods for the traffic algorithms. This concrete sub-chapter created a knowledge base for further methodology definition. In the last part of the literature review, the current state of traffic management reducing the congestion incidents is reviewed.

2.1 TRAFFIC DATA ANALYSIS

The aim of this chapter is to provide an overview of characteristic properties of the capacity value. Besides that, special focus is put on a concept of the capacity definition. Clarifying this term ensures the unambiguity and helps to better understand the theoretical base of this master thesis. Additionally, some relations between the common traffic parameters and the capacity are mentioned.

2.1.1 CAPACITY OF FACILITY – DETERMINISTIC VALUE

Traditional approach construes the capacity as a deterministic value. This logic has been widely employed in the traffic management tools.

The most common definition, plentifully referenced in the transportation literature, comes from the statements presented at Highway Capacity Manual HCM (2000). According to this definition, the capacity represents the maximum number of vehicles or passengers that may pass a uniform section of a roadway at given conditions and time period. Also the passenger capacity and vehicle capacity might be separately defined. A role of the conditions on the capacity will be discussed later (see chapter 0).

Minderhoud et al. (1997) described the capacity of facility definition (as was stated above) as a tool for traffic planning and road designing; additionally they define the following terms:

- Strategic capacity:
- A capacity value, derived for example from fundamental diagram (Figure 1),

obtained for specific traffic engineering purposes as traffic flow assignment or simulation.

- Operational capacity:

  Whereas the previous determinations considered the static capacity models, an operational capacity value is linked to topical traffic volumes. In this manner, the operational capacity is interesting in terms of traffic management tools.

2.1.2 CAPACITY AS DETERMINISTIC VALUE – PROPERTIES

The idealistic traffic fundamental diagrams (see Figure 1) that is known for more than 75 years, determine the relation between the basics traffic variables – flow rate q [veh/h], density k [veh/km] and speed v [km/h]. As one would expect, known values of two variables (for example speed and density) allowing to compute the third one: $q = k \cdot v$. The traffic engineering have been used these essential relations (widely presented in the traffic engineering literature) to describe the specific static situations.

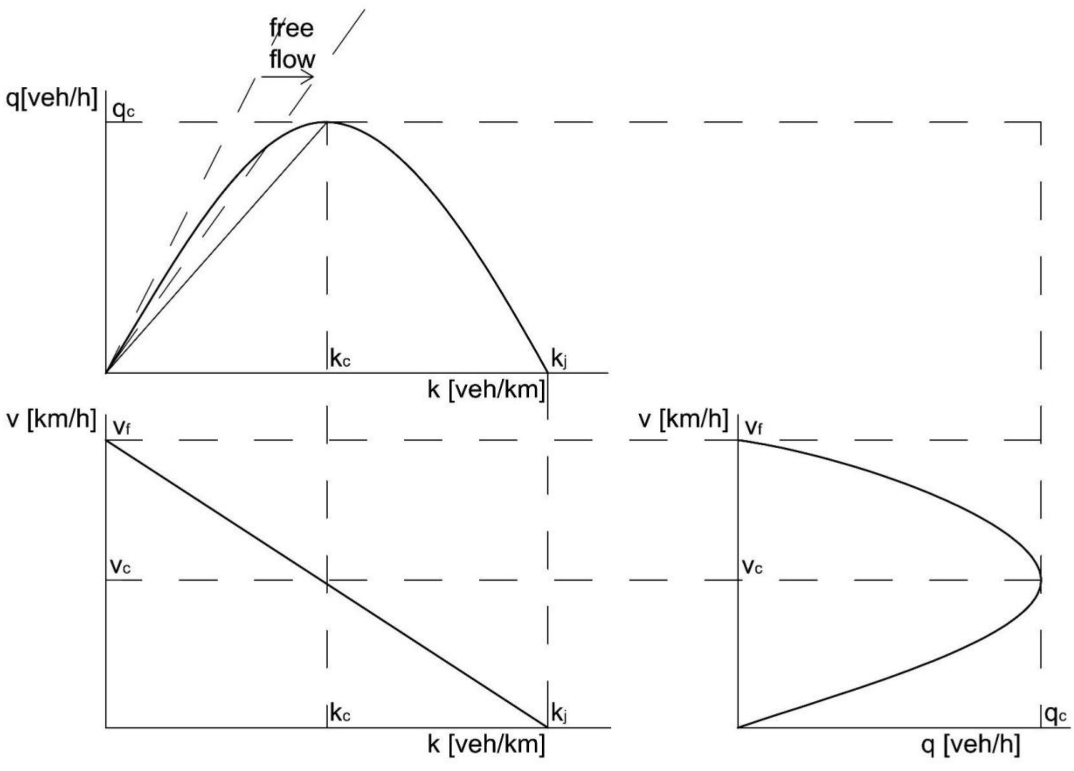

Figure 1: Traditional fundamental three traffic models diagram

Lighthill and Whitham built an ideal model as it is presented above (see Figure 1), consisting of a linear relation velocity-density and two parabolic relations traffic flow-density (global positive extreme denotes maximum capacity) and velocity-traffic flow Kühne (2009). They preceded their research on PhD thesis of Greenshields who is commonly considered as a founder of q-k-v model. However, Greenshields initially used a triangular relation between traffic flow and density. One interesting fact regarding the traffic situation description is revealed by the q-v chart: as a parabolic characteristic implies, there are two “regimes” of speed for a one level of traffic flow. Thus, the chart might be researched and separate into a stable and an unstable regime Kühne (2009).

Using the traditional fundamental diagram, Immers & Logghe (2002) differentiated various traffic situations into the three main traffic “regimes”:

- Free Flow regime:

  This regime (see Figure 2) is characterized by density upper bounded by k_c and the speed values approaching their maximum v_f. Another typical indicator is a positive value of $q'(k)$ in q-k chart that implies increasing capacity. In that case, speed is only reduced by roadway geometry or by a temporary speed reduction.

- Capacity regime:

  The capacity regime (see Figure 3) stands for the concept of deterministic capacity value as was defined before (chapter 2.1.1). Looking at the flow rate-density relation, one might clearly see the flow rate reaches its maximum q_c. The first derivation of traffic flow rate $q'(k)$ is equal to zero. A roadway stretch, where it exceeds its maximum number of vehicles passes through is sometimes referred as the saturation state. Compared to the previous free flow regime, the speed has decreased on the value v_c and density has increased on the value k_c.

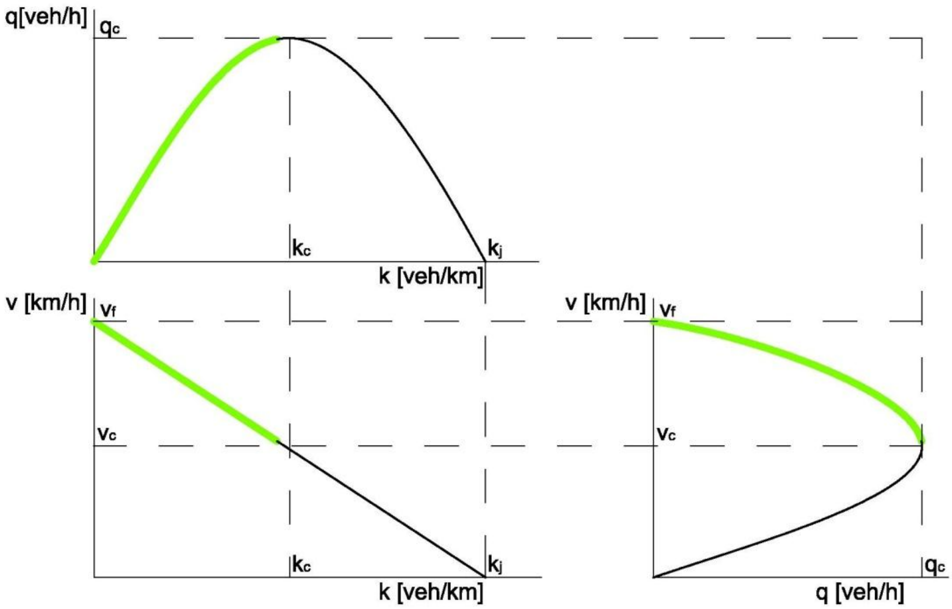

Figure 2: Free flow regime

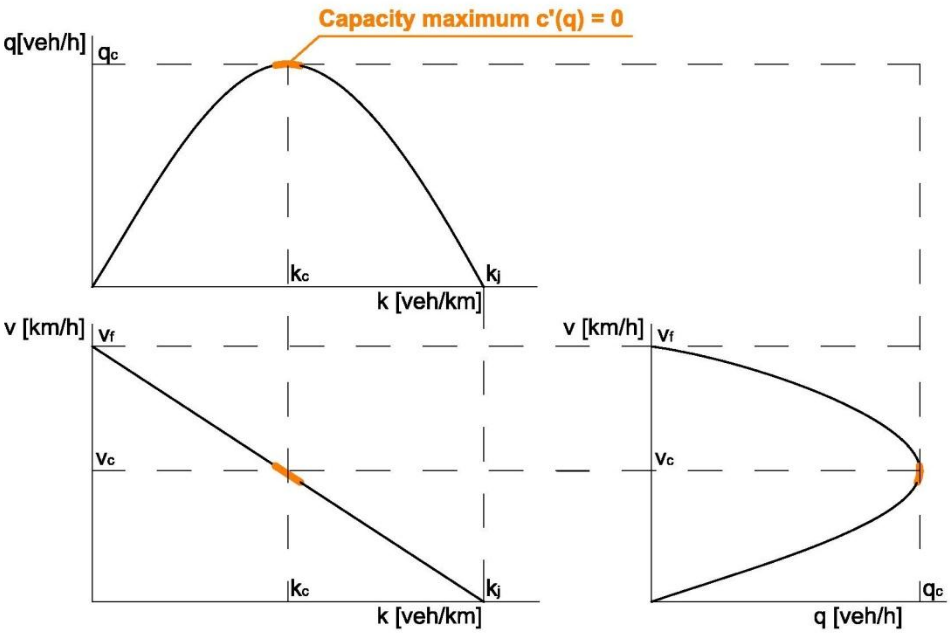

Figure 3: Capacity regime

- Congested regime:

The combination of speed reduction and aggravated density is results in the congested regime represented by the values v_j and k_j which approach zero. From the flow rate-density relation might be observed that flow rate decreases and approaches to zero after passing the roadway capacity at the point q_c (see Figure 4).

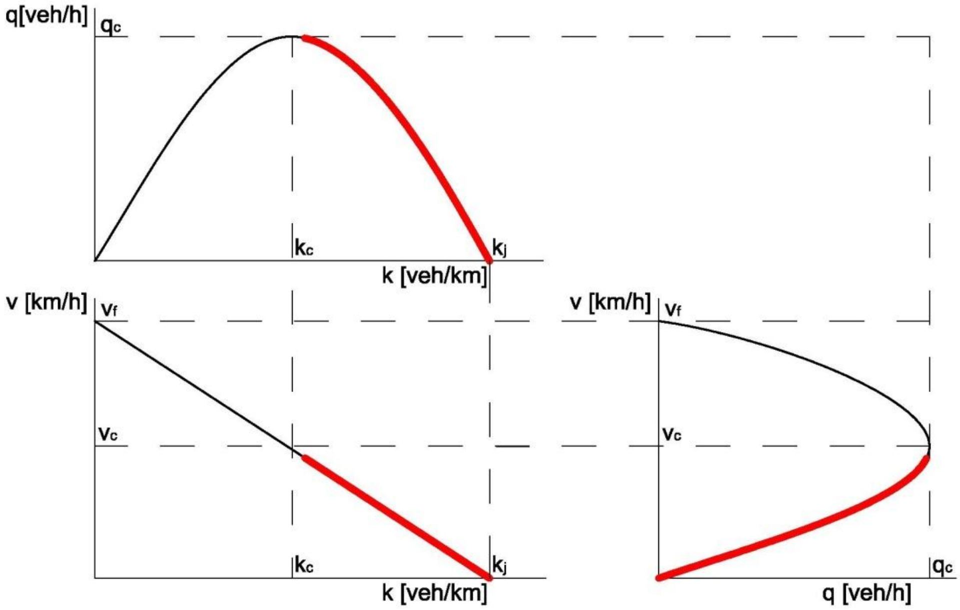

Figure 4: Congested regime

Note that since capacity has reached its maximum at previous capacity regime, the jam regime is characterized by decreasing capacity and increasing density.

The congestion regime is commonly linked to the speed values of the vehicles. For this purpose, the speed-flow rate is divided in the fields marked by numbers, representing a specific “traffic state”. The traffic state is rather more simple term that is pro-user oriented. The techniques of such field classification are linked to the national standards and policies. For example, the Czech Republic recognizes between 1 (best) and 5 (worst) whereas USA classify six states, so-called Level of Service (LOS) from A (best) and F (worst) HCM (2000).

2.1.3 CAPACITY OF FACILITY – STOCHASTIC VALUE

The deterministic description of capacity facilitates an intuitive description and with the fundamental traffic diagram together constitutes a potentially effective tool for traffic engineering.

However, the empirical results proved that capacity as deterministic value does not trustworthy represents a real situation. This statement has been concluded by the several authors, e.g. Minderhoud et al. (1997), Persaud et al. (1998), Brilon (2000), Okamura et al. (2000), Lorenz & Elefteriadou (2001), Brilon & Geistefeldt (2009), Schwietering & Steinauer (2011) etc.

Basically, it has been showed the traffic breakdowns occur at a variety of the flow rates directly preceding a breakdown and therefore the maximum volume passing the road section is not a constant value. The better understanding requires a clarification of the traffic breakdown term. Brilon et al. (2005) stated that the traffic breakdown is a transition from the acceptable flow rate values (free flow state) into the non-acceptable flow rate values (congested conditions). In the other words, the breakdown occurs in the case when vehicle speed has shifted from the free flow speed (determined by the road geometrics or alternatively by the means of speed reduction established by a road operator) to the speed representing the congestions, e.g. speeds below the 50 km/h for the Germany highway as was stated by Bogenberger (2004). An example of traffic breakdown is shown in the figure below (see Figure 5). A traffic breakdown occurred within one measured interval (16:25 – 16:30) that is directly preceded by an increase in flow rate. Brilon & Geistefeldt defined for the purpose of their study a speed threshold of 80 km/h. In this manner, one might observed two more breakdowns at 17:05 and 17:30. Whereas the breakdown at 16:25 stands for a drop from free flow into congested condition, the other two transitions show just a short traffic recovery during congestion and therefore they are not considered as breakdown. This situation implies the difficulties in a traffic breakdown employment. To reduce the drawback mentioned above, Brilon & Geistefeldt (2009) applied so-called five criteria where five restrictive conditions (see the equations a – e below) for preceding/following velocity values to an investigated interval are used in order to filter out the recoveries.

a) $v(i-1) > v_t$
b) $v(i) > v_t$
c) $v(i+1) \leq v_t$
d) $v(i+2) \leq v_t$
e) $0.5 \cdot [v(i-1) + v(i)] - 0.5 \cdot [v(i+1) + v(i+2)] > 10$ km/h

The first four conditions (a-d) comparing actual velocity values during the successive time intervals (v_{i-1}, v_i, v_{i+1}, v_{i+2}) with a reference traffic breakdown velocity threshold value (v_t) and additionally the fifth condition (e) of a minimum 10 km/h speed reduction between the two intervals before and after the breakdown was defined. The traffic breakdown is observed if all five conditions are fulfilled. Note that Brilon & Geistefeldt used a five-minute interval in their research.

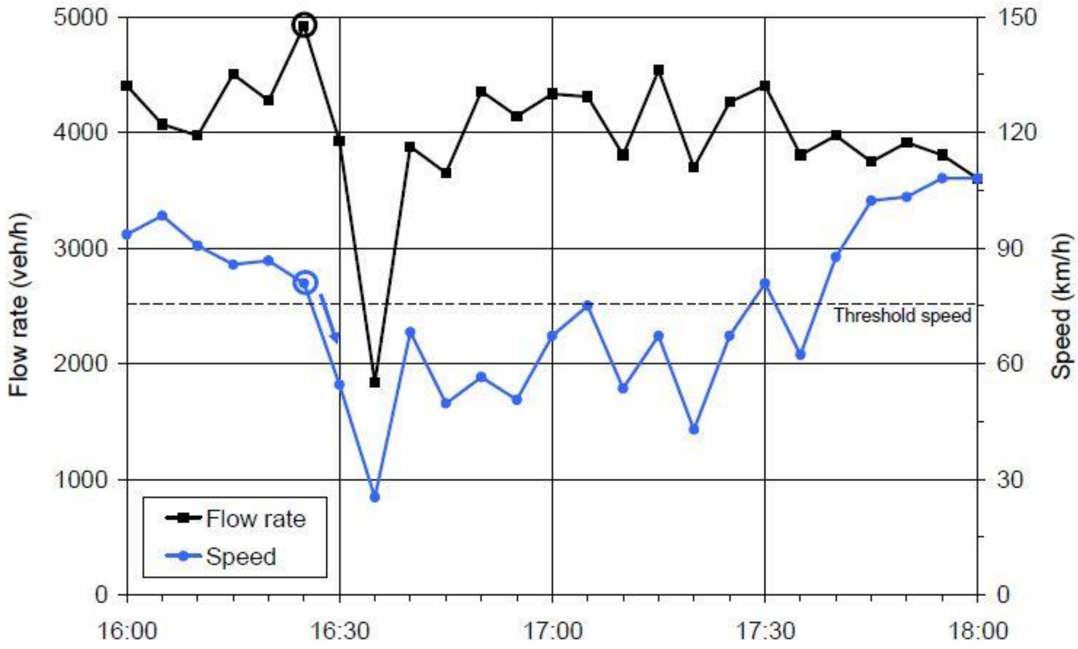

Figure 5: Example of traffic breakdown, source: Brilon & Geistefeldt (2009)

The randomness of the traffic breakdown, even under the constant traffic conditions, insinuates the stochastic nature of capacity and point out imperfection of the fundamental diagram.

An origin of the stochastic nature of capacity is not really clear and requires further comprehensive researches. As was stated at Minderhoud et al. (1997), the factors like human behavior or weather conditions have an influence on the capacity randomness, however, the sufficient theoretical proves are missing.

2.1.4 CAPACITY OF FACILITY – STOCHASTIC VALUE EMPLOYMENT

To employ a stochastic concept of capacity, the capacity distribution has to be defined. Some of the methods how to determine the distribution functions were described in Brilon & Geistefeldt (2009) in detail.

The author restricted the master thesis focus on the explanation stated by Schwietering & Steinauer (2011). This concept, sometimes referenced as “direct breakdown probability estimation” Brilon & Geistefeldt (2009), is based on the relation between the number of the capacity events (traffic breakdowns) and the number of intervals at the fluent traffic. This ratio just characterizes the probability of the traffic breakdowns:

$$F_{Cj}(q) = p_{Cj}(c_j \leq q)$$

$$p_{Cj} = \frac{m_j}{n_j} \quad \text{, where } m_j \in n_j$$

F_{Cj} …Capacity distribution function

p_{Cj} …probability of the traffic breakdown under the a volume j

m_j …number of capacity events

n_j …number of intervals at fluent traffic

q …traffic flow rate

The distribution function (in this case as a product of AIX-ProB algorithm) is showed at Figure 6. The picture clearly illustrates one property of probabilistic approach: whereas using the fundamental diagram (specifically Van Aerde model is used on the chart below) carries out two different values of velocity for one traffic rate, analyzing the probability of breakdown curve obtains unambiguous result for maximum "demanded flow rate" (capacity).

2.1.5 Capacity – Influencing Conditions

As was stated before, the capacity values vary under the given conditions. Unfortunately, there are no robust models available at the moment that would describe the conditions and their specific impact on capacity. However, some empirical studies devoted to this problem were accomplished, for example Okamura et al. (2000), Kyte et al. (2000), HCM (2000), Schwietering & Steinauer (2011).

Kyte et al. (2000) performed extensive research in Idaho and afterwards identified the four main factors influencing the vehicle speed. Comparing data collected during the specific conditions with the data obtained during the base conditions (no precipitation, dry roadway, visibility > 0.37 km and wind speed < 16km/h), the authors came to the results presented at Table 1. Results presented in the table indicate an expected effect of the unfavorable environmental conditions. Furthermore, Kyte at al. have developed the model for each of the variables, however, the comprehensive tests and verifications proved the model's robustness (and thus possible larger employment) are not available.

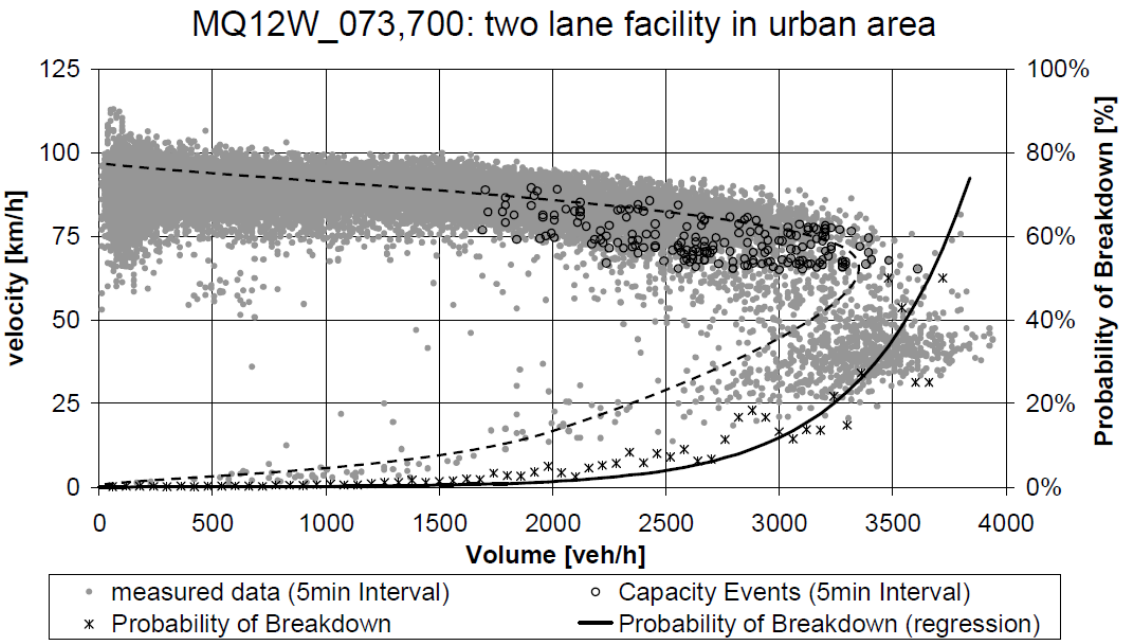

Figure 6: Comparison of between fundamental diagram and the probability of breakdown, source: Schwietering & Steinauer (2011)

Table 1: Aggregated effect of environmental factors, source: Kyte et al. (2000)

Variable	**Range**	**Mean speed, fog days, km/h (obs*)**	**Mean speed, snow days, km/h (obs)**	**Mean speed, all days, km/h (obs)**
Visibility	0.0 – 0.16 km	92.4 (53)	39.6 (21)	77.4 (74)
	0.16 – 0.37 km	101.0 (110)	50.7 (90)	79.7 (200)
	> 0.37 km	106.8 (306)	85.9 (1140)	90.8 (1446)
Road surface condition	Dry	107.2 (126)	85.1 (128)	96.1 (254)
	Wet	-	85.7 (256)	85.7 (256)
	Snow/Ice	98.7 (81)	73.3 (194)	81.9 (275)
Precipitation intensity	None	103.8 (469)	100.7 (20)	103.7 (489)
	Light	-	83.1 (335)	83.1 (335)
	Medium	-	80.1 (169)	80.1 (169)
	Heavy	-	77.1 (54)	77.1 (54)
Wind speed	0 – 16 km/h	103.7 (458)	91.7 (93)	101.7 (551)
	16 – 32 km/h	107.2 (11)	103.7 (233)	103.8 (244)
	32 – 48 km/h	-	83.2 (557)	83.2 (557)
	> 48 km/h	-	55.3 (368)	55.3 (368)

**obs* is the number of observations.

In order to investigate the role of factors on capacity and LOS, HCM (2000) listed following factors:

- Road conditions

  The conditions coming from roadway and its geometry, for example number of lanes, type of facility, lane widths, design speed, shoulder speed and lateral clearances and availability of exclusive turn lanes at intersections.

- Traffic Conditions

  The negative impact of heavy vehicles was mentioned particularly because heavy trucks occupy more space and they have worse driving performance (comparing to the passenger vehicles). The directional and lane disruption effect was revealed.

- Control conditions

  Consider the control conditions the most severe effect is mainly linked to the traffic signals.

Although HCM (2000) presented an extensive study of conditions influence on traffic (flow rate and speed), the numerical results regarding capacity are missing. In this context, the research undertaken by Schwietering (2010) is remarkable. Schwietering analyzed voluminous data (approximately 700 highway sites in Austria) and subordinate them to the reliable statistic methods. Concretely, by using the multiple variance analysis ANOVA, a significant influence of the related factors on capacity was proved. Based on this conclusion, the regression curves for the probability of breakdown for every possible combination of influencing factors were derived and then used as referenced capacity distribution curves for the AIX-ProB algorithm (for more detail description of the Schwietering's algorithm see the chapter 3.1). Schwietering & Steinauer (2011) summarized influencing factors into:

- Constant influencing factors on capacity.
- Temporary influencing factors on capacity.
- Influencing factors on capacity based on traffic control management applications.

The presented results of analysis are showed in Table 2. Since the quantitative values were obtained, a specific curve determining the probability of breakdown can be discovered with respect to the site's factors. The resulted values in the table are referenced to the ideal conditions (weekday, daylight and dry surface conditions).

Table 2: Factors influencing capacity, source: Schwietering & Steinauer (2011)

No.	Group	Parameter	quantitative values *
1-1	constant factors	urban area vs. rural area	+ 6,3%
1-2		grade terrain	**- 13,4% ****
2-1	temporary factors	wet surface conditions	**- 14,4%**
2-2		day/night	**- 14,1%**
2-3		weekday/holiday	**- 5,7%**
3-1	control factors	Corridor Management Application	+ 3,5%

*: given values represent deviation in comparison at ideal conditions such as dry surface conditions at daylight on a weekday

**: grades von 3% in comparison to level terrain

2.2 EVALUATION METHODS FOR THE TRAFFIC ALGORITHMS

This chapter provides a theoretical base for the further research of evaluation methods for the traffic breakdown predicting algorithms. In general, the range of methods for evaluation general traffic algorithms could be considered relatively broad (including issues like data quality, algorithm consistency or its impact on traffic). Unfortunately the practical guideline for traffic control algorithms (or even for particular scope of the algorithms predicting the traffic breakdowns) is missing.

The evaluation methods for the control algorithm using traffic breakdown predictions should assist in the answering questions like:

- Does the proposed algorithm improve the traffic situation?
- What is the capacity benefit?
- Is there any kind of benefit on the traffic safety?
- Does the algorithm have capabilities to being applied across the large road network?
- What is the algorithm’s ability to predict the traffic flow incidents?

Indeed solving these fundamental issues is not trivial and it requires systematical approach which considers the user and provider needs, available means, data etc.

2.2.1 EFFECTIVENESS OF THE TRAFFIC CONTROL

Hoops et al. (2000) outlined the assessment criteria for the recognition procedures of the disruptions in traffic. The criteria were formulated in order to investigate the effectiveness of such systems and additionally, the assessment was undertaken on 14 procedures. The criteria were differed into:

- Operative criteria
    - Recognition quality.
    - Error tolerance (deal with a problem of system application possibilities over the erroneous data sets).
    - Dependence of the quality on the detector distance.
- Implementation and Cost Aspects
    - Needs for technical equipment.
    - Initial outlay.
    - Miscellaneous costs for the system implementation.
    - Regular expenses linked to the system maintenance.

Considerable effort was developed to research the recognition quality aspects of the detection procedures. It was defined in Hoops et al. (2000):

$$\text{Detection rate (drops in speed)} = \frac{N(A \cap E)}{N(E)}$$

$$\text{False-alarm rate} = \frac{N(A \setminus (E \cup U \cup B))}{N(A)}$$

$$\begin{array}{ll} A & \ldots\text{alarms} \\ B & \ldots\text{roadworks} \\ E & \ldots\text{drops in speed} \\ U & \ldots\text{registrated accidents} \end{array}$$

The measure $E \cup U \cup B$ "filters out" the static disruptions (road constructions and accidents) in order to obtain the realistic values for false-alarm rate (avoiding the value overestimation). Obviously the indicators defined above oppose one another; the optimum procedures show high detection rate while high false-alarm rate disqualifies the traffic control system. However, the concrete numerical recommendations for the detection and false-alarm rate regarding the specific drops in speed are missing.

The detection and false-alarm rate was also presented by Bogenberger (2004) who used the graphical interpretation of the rates in the traffic information quality investigation (see chapter 2.2.2). Using an idea of the rates establishes a solid method for the evaluation of overall traffic control quality (see chapter 4.4.3).

Further research was brought by Steinhoff et al. (2002) and it aimed on the preventive variable speed limits in dynamic speed management systems concerning the system effectiveness.

Moreover, Steinhoff et al. (2002) observed a relation between the target vehicle speed and the preventive variable speed as the compliance. The compliance could be presented on the fact that a displayed reduction by 10 km/h impacts the vehicle speed by 2 km/h. There are number of factors (e.g. various weather or road conditions) that influence the target vehicle speed, obviously fundamental is the effect of drivers' behavior (some sociological aspects were revealed in the book).

2.2.2 QUALITY OF TRAFFIC INFORMATION

Although the following research was focused on the traffic information, some statements and principles would be applicable on traffic control systems (variable speed limits). The technique of such utilization is going to be discussed further (see chapter 4).

The quality of the traffic messaging was investigated by Bogenberger (2004). The typical problem is trustworthiness of traffic information messages, therefore Bogenberger identified as a main question, regarding the quality, the spatial and time message relevance. In the other words, if the system delivers the traffic message to a driver at the wrong time (earlier/late) or at if the system transmits the traffic message to a driver at incorrect position, the operability of such service collapse because no-one is going to follow them anymore. The approach presented in the paper offers a strong tool for visualizing traffic situations (see Figure 7) where numerical interpolation over the time-space relationship is carried out. Subsequently unambiguous evaluation using the pre-defined quality indexes is applied.

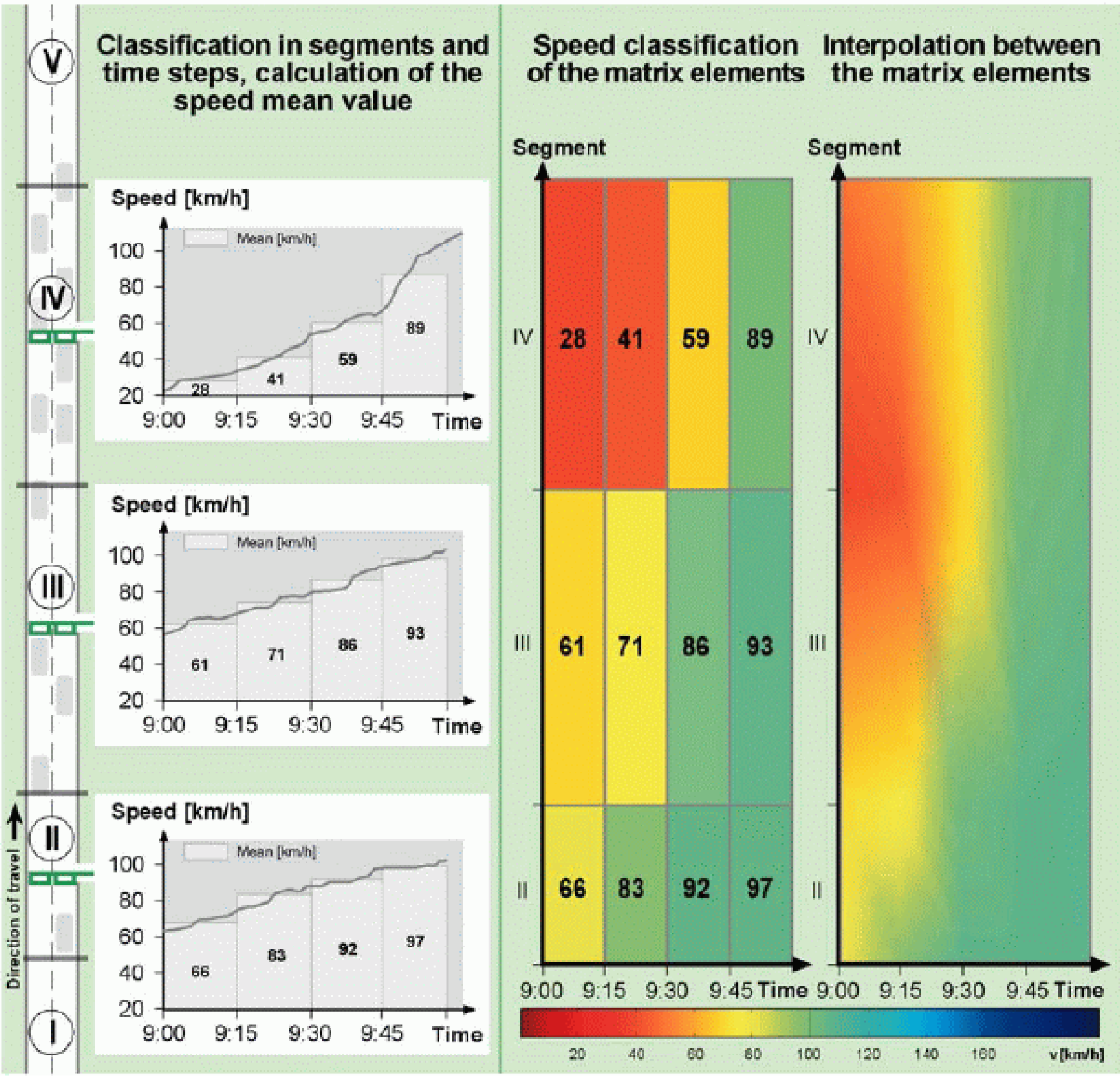

Figure 7: Description of the traffic situation, source: Bogenberger (2004)

2.2.3 Traffic Information – Quality Indexes

Bogenberger (2004) defined the following quality indexes in order to qualify the message of spatial and time relevance:

$$\text{Detection rate} \qquad QKZ_1 = \frac{D}{E}$$

$$\text{False-alarm rate} \qquad QKZ_2 = 1 - \frac{D}{A}$$

A …area of broadcasting traffic messages

E …area of the congestion

D …intersection of area A and E

Note that the indexes are defined in the same fashion as the quality aspects in chapter 2.2.1 where the set notation was transformed into an intuitive description using the accurate areas representing for a particular state (see Figure 8).

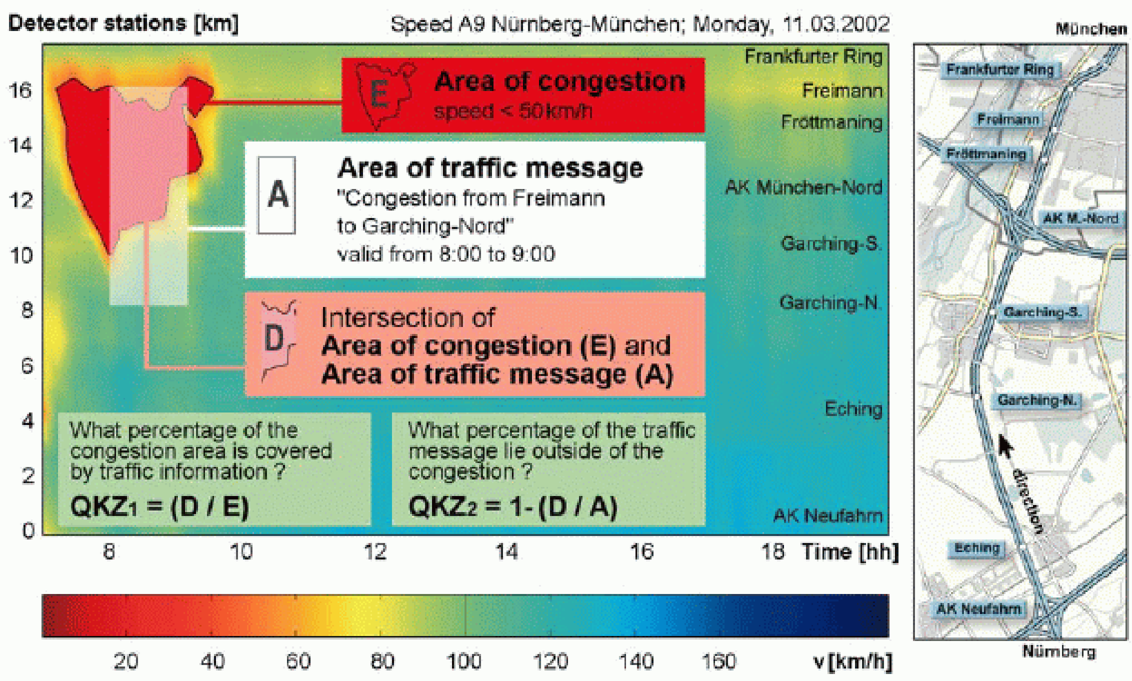

Figure 8: Quality indexes, source: Bogenberger (2004)

2.2.4 Traffic Information – Assessment Technique

It was developed the 6 grade scale, from A (very good) to F (poor) that was utilized in quality traffic information assessment in order to make the result presentation easy to understand. This scale was applied on the two axis system where the quality index QKZ_1 is put on y-axis and the index QKZ_2 is put on x-axis (see Figure 9).

To carry out the clear assessment, Bogenberger uses the extreme cases placed in the corners of mesh. Here is their brief explanation:

- Case 1

This case might be understood as a positive extreme. The index QKZ_1 is equal 100 % and QKZ_2 is approaching the zero. All events are then covered by traffic message and the system produces no redundant traffic message.

- Case 2

In this case, the area A is much smaller than the area E, their common intersection is zero. The indexes QKZ_1 and QKZ_2 are equal to zero. This resulting situation might be interpreted as a small "information effort" created by the system. Bogenberger assigned grade F to this specific situation

- Case 3

Another extreme example evaluated by grade F. Here is the messaging area A much bigger than the congestion area E ($QKZ_2 = 1$). Nevertheless the intersection of E and D is equal to E and thus $QKZ_1 = 1$. This constellation results in allocation of the Case 3 in top-right corner.

- Case 4

The last case represents the situation when the information message A is broadcasted outside of the area D. This particular example is potentially dangerous since one group of drivers (outside the area D) receives information about non-existing congestion whereas relevant information about the coming congestion is not delivered.

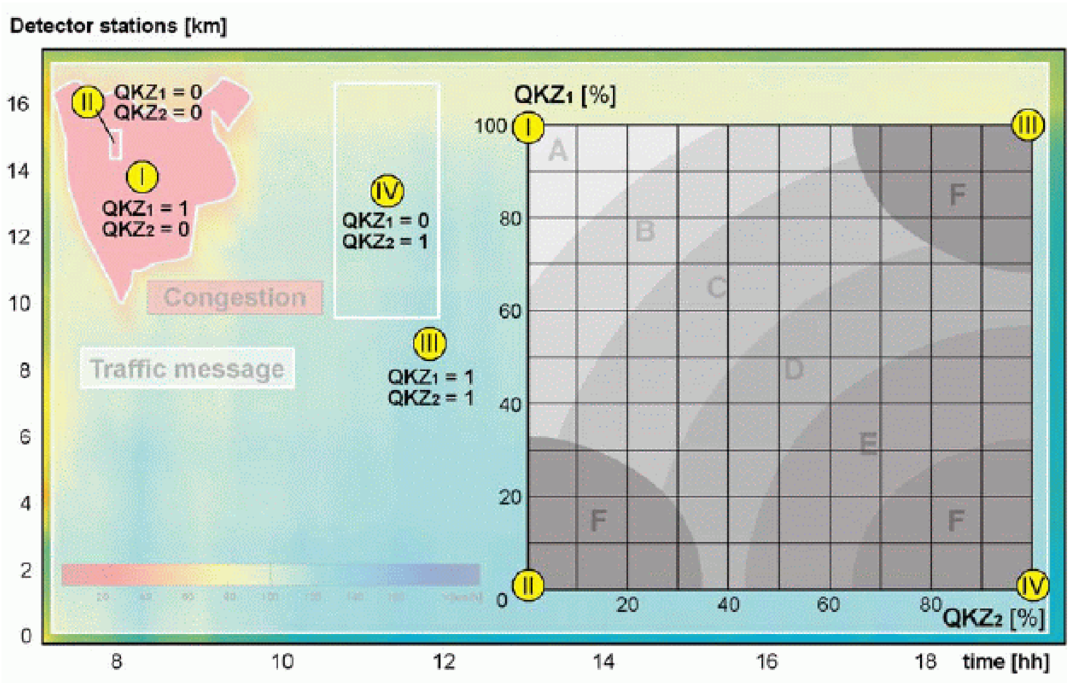

Figure 9: Grading system and extreme cases at quality diagram, source: Bogenberger (2004)

One may see that the methodology developed by Bogenberger provides simple and very illustrative way how to assess the information service quality.

2.2.5 TRAFFIC INFORMATION – ERRORS CATEGORIZATION

As implied in chapter 2.2.4, several causes of error might be identified. The system provides accurate traffic information message regarding not only the content and technical specification but also the spatial and time relation that appears as crucial to make the system operable and beneficial for user. Naturally, the framework of the system evaluation (error assessment) is going to be different for the algorithm predicting traffic breakdowns which is a part of the traffic management systems.

Bogenberger (2004) distinguishes between:

- Errors caused by wrong system performance (see Figure 10, errors number 1 and 2)
- Time-oriented errors (see Figure 10, errors number 3 & 4)
- Spatial-oriented errors (see Figure 10, errors number 5 & 6)

It was stated, the error types 1 and 2 have the most severe impact from the user point of view.

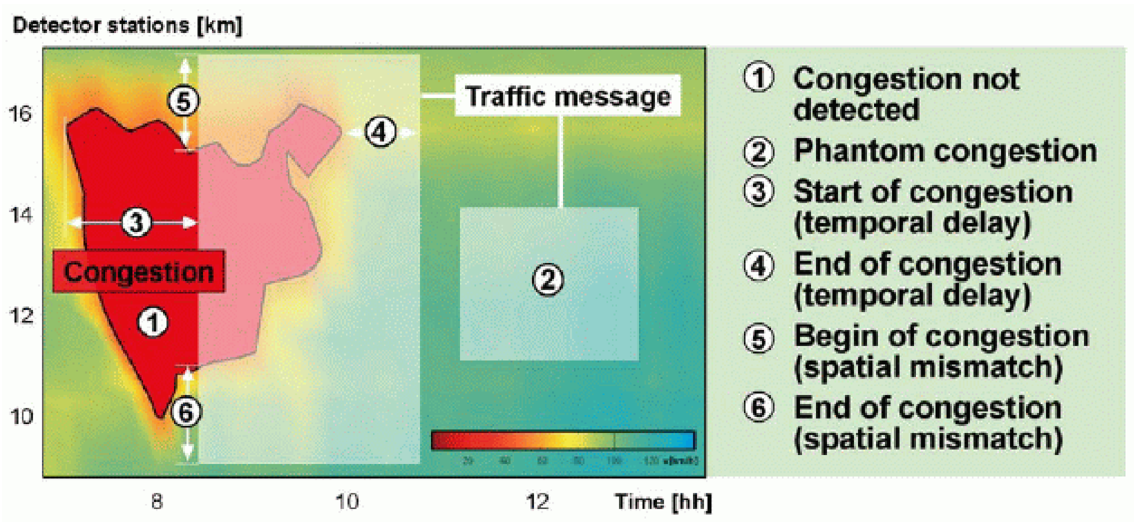

Figure 10: Errors categorization, source: Bogenberger (2004)

2.3 ANALYSIS OF THE CURRENT STATE OF THE TRAFFIC MANAGEMENT TOOLS FOR THE REDUCTION OF BREAKDOWNS

A goal of this chapter is to research the current state of the traffic management tools and strategies. The increasing traffic demand, which is causing "traffic problems", has raised the need for the maximizing the utilization of freeway capacity. If one desires to preserve a specific level of mobility and rejects the futility of current roadways, then the modern

Intelligent Transportation Systems (ITS) has to be deployed. The deployment of ITS in USA can be clearly observed from Figure 11. The term "traffic problems" mentioned above does not cover only a capacity issue (congestion occurrence) but it is also linked to a question of:

- Traffic safety.
- Travel time.
- Externalities (e.g. environmental impact).

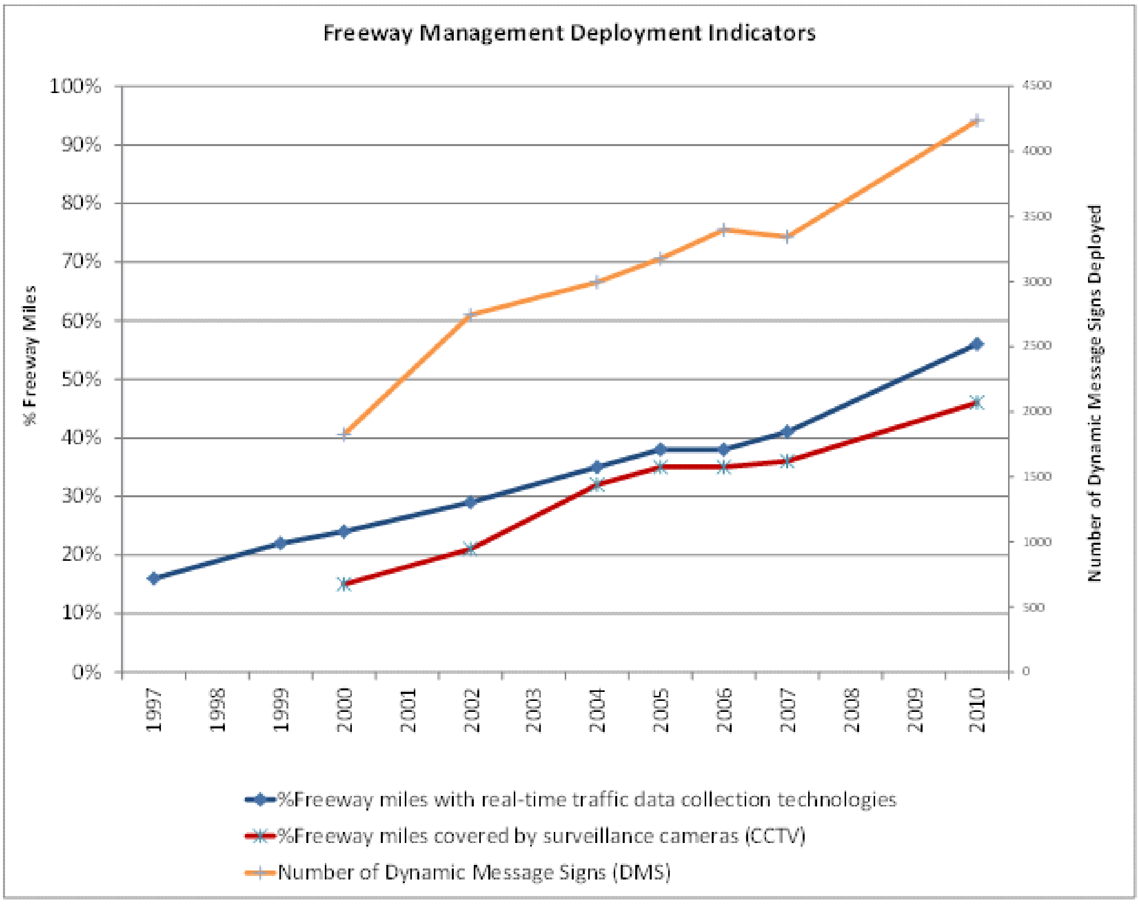

Figure 11: Development of some infrastructure ITS in USA, source: RITA (2011)

2.3.1 TRAFFIC MANAGEMENT STRATEGIES

A framework of presently using active traffic management (ATM) systems is outlined at the figure below (see Figure 12). The AIX-ProB can be considered then as a variable speed limits (VSL) tool belonging to the increase of capacity strategy. However, an intersection of strategy and management objectives is strongly dependent on a used span; whereas Michaelsen & Přibyl (2009) allocate only a congestion regulation objective to lane management, Neudorff et al. (2006) stated several examples where larger benefit by deployement the VSL is achieved. Neudorff et al. (2006) introduced an example from succesful highway VSL system in the Netherlands. There the VSL gates (obvioulsy embeeded by lane control) distributed every 500 meters prooved collision reduction about 16% and increased throughput 3 – 5%. Certain exteranilty benefit can be viewed in a cost reduction for utilizing VSL at work zones (instead of extra traffic control).

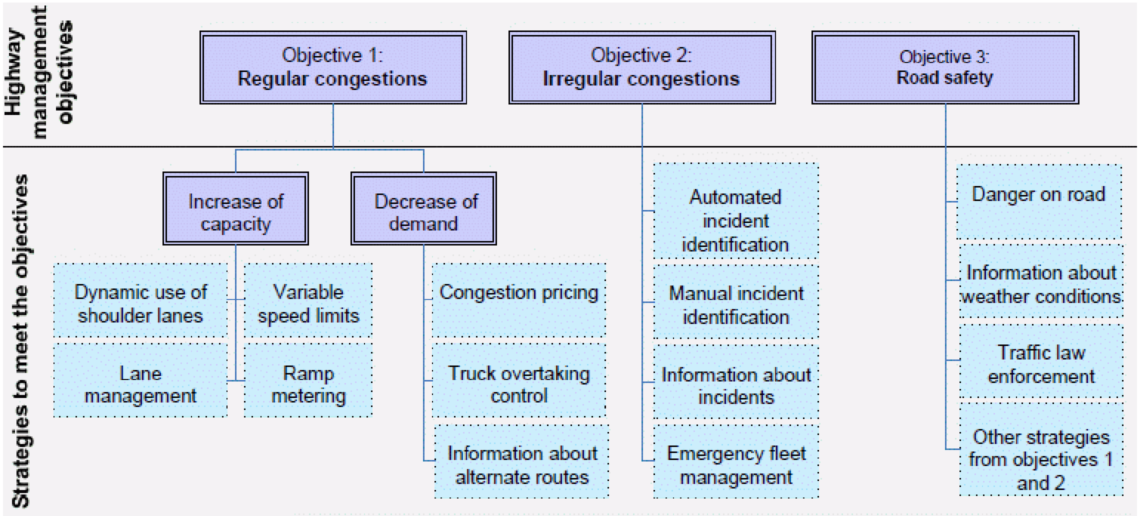

Figure 12: Highway traffic management strategies, source: Michaelsen & Přibyl (2009)

Mirshahi et al. (2007) presented the following table (see Table 3) that aims on the particular benefits of the concrete lane management strategies which are typically deployed in Europe. When it comes to freeway performance improve (in wider sense, from the safety issues to flow rate incensement), summary below gives to one a clue which systems fulfill the expectations. Note that the positive impacts described in the table are linked to the strategies rather as to the stand-alone technologies, whereas in real practice the synergy effect from using several systems might be obtained.

Table 3: Traffic lane management strategies benefit, source: Mirshahi et al. (2007)

Active Traffic Management Strategy	Potential Benefits												
	Increased throughput	Increased capacity	Decrease in primary incidents	Decrease in secondary incidents	Decrease in incident severity	More uniform speeds	Decreased headways	More uniform driver behavior	Increased trip reliability	Delay onset of freeway breakdown	Reduction in traffic noise	Reduction in emissions	Reduction in fuel consumption
Speed harmonization	•		•		•	•	•	•	•	•	•	•	•
Temporary shoulder use	•	•							•	•			
Queue warning			•	•	•	•	•	•	•		•	•	•
Dynamic merge control	•	•	•			•		•	•	•	•	•	•
Construction site management	•	•							•		•	•	•
Dynamic truck restrictions	•	•				•		•	•			•	•
Dynamic rerouting and traveler information	•		•	•				•	•			•	•
Dynamic lane markings	•	•							•				
Automated speed enforcement			•		•	•		•	•			•	•

2.3.2 European State of Traffic Management Tools

The deployment of traffic management tools is not roofed by any European standards or norms. In this manner, the used strategy, technology and system settings are particular responsibility of the national road operators. For example, the German and Austrian road operators based their systems primarily on research undertaken by MARZ99 (1999). The latest available plan for deployment of ITS in Europe stated: “The response to those major challenges cannot be limited to traditional measures, inter alia the expansion of the existing road transport infrastructure. Innovation will have a major role to play in finding appropriate solutions for the Union” Parliament Council European (2010). Despite the need to maximally utilize capacity of current facility, the directive does not specify any parameters for ATM.

Since there is no pan-European ITS deployment directive for highway traffic management, the national development level and successes they have achieved are considerably different. This development was partly documented in Mirshahi et al. (2007). Within this project, the approach in congestion avoiding strategies for highways was researched at Denmark, England, Germany, Greece and the Netherlands where an overall positive effect on capacity was expressed (incensement about 3 - 22% depending on the national’s strategy). As a significant transportation technology developer and a state with one of the largest highway network in Europe, Germany has employed following ATM strategy:

- Speed harmonization

Speed harmonization or lane control is a strategy that has begun to been build 40 years ago and proved its benefit not only in traffic flow optimization. In addition, safety impact can be presented on the local motorway A5 survey (Bad Homburg – Frankfurt/West). It had showed decrease about 30 % in human injuries Mirshahi et al. (2007).

- Queue warning

The speed harmonization system was enhanced by queue warning. System is arranged on the highway gantries. It had suddenly achieved positive effect in safety (severity of accidents), harmonizing the traffic flow and uniform driver behavior drives.

- Temporary shoulder use and speed harmonization

The strategy aims on temporary capacity incensement by opening a right lane. It is typically use within the congestion and significant speed reduction incidents. However, practice showed some drawbacks (externality costs) and therefore a special software tool, which decides when and where to use temporary shoulder was developed.

Mirshahi et al. (2007) further presented some other strategies used in Germany, for example ramp metering, junction control, construction site management etc. Similar technologies nevertheless with a different level of deployment are identified for the other studied countries.

2.3.3 DYNAMIC SPEED REDUCTION STRATEGY

In the previous chapter (see chapter 2.1.3), the doubts about traditional explanation of capacity were presented. Consequently stochastic capacity nature is presented together with fair literature reference which empirically proves this theory. Considering acute need of maximum capacity on freeways, as it is emphasized at Parliament Council European (2010) or Mirshahi et al. (2007), one might expect major implementation of the traffic management systems using stochastic approach by the national road operators. However, the author has not found any study that would assess a usage of such a strategy on the national level. If one sticks to the Germany practice, Boltze (2006) pointed out that the actual German highway capacity manual (HBS) still uses the traditional approach to determine capacity. More specifically, so-called 30th hour rule is applied as decisive factor.

Traffic statistics and their subsequent use in the level of service determination employ the "relevant" hourly flow rate that is equal to 30th highest flow measured per year. An example of a traditional strategy is showed on the figure belowed (see Figure 13). The speed reduction system is enhanced by the lane alignment control. It is evident that traffic volume is the main determining factor with no respect to the stochastic nature of capacity. Moreover, the control is undertaken regardless to any capacity influencing factors.

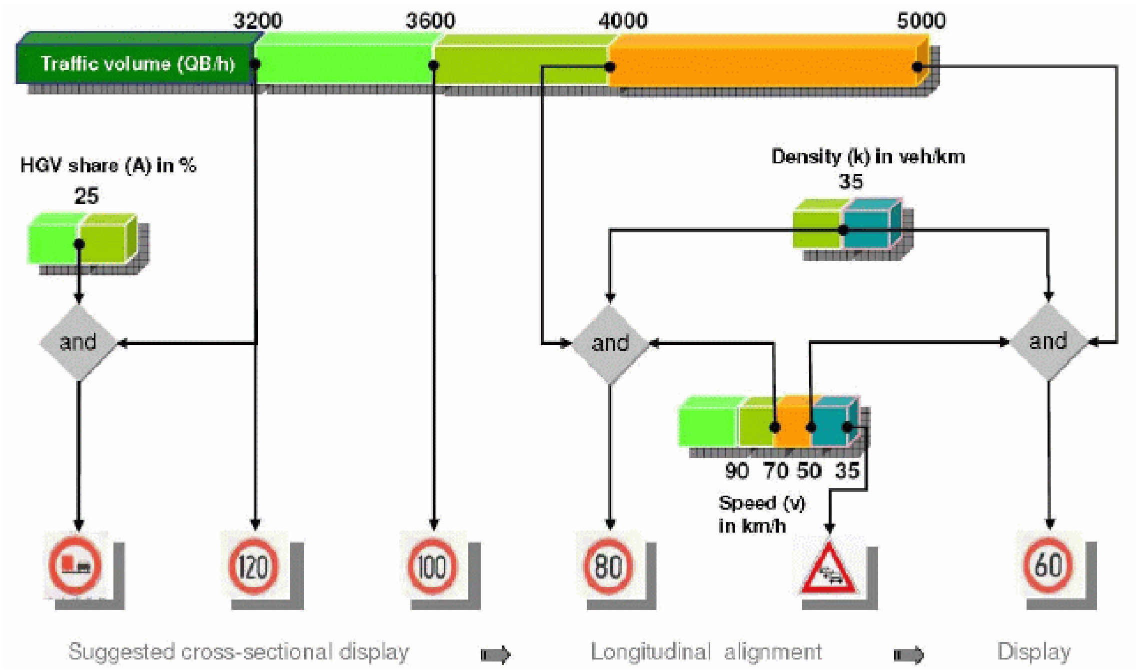

Figure 13: ATM in Germany, source: Dale et al. (2009)

A lack of practical experience with stochastic capacity approach as a speed reduction control strategy just expresses a need for an evaluation methodology. The evaluation can unambiguously answer the question of benefit coming out of this strategy. In order to achieve the successive assessment, the new evaluation methods and the related metrics (see chapter 4) has to be developed.

2.4 SUMMARY OF THE IMPORTANT LITERATURE OVERVIEW FINDINGS

At the beginning of the chapter 2.1, the fundamental concept of highway capacity and its basic properties were presented. Regarding the number of empirical researches, tt was referred (see the beginning of sub-chapter 2.1.3) that the deterministic concept of capacity has some limitations. The author thus made a step towards the stochastic theory of capacity that erases previous difficulties. A probabilistic approach for stochastic capacity is going to be further used as a necessary prerequisite for the AIX-ProB algorithm. In order to employ the probabilistic approach, the author shows the probability breakdown formula as an effective way for determining the actual capacity values (discussed at chapter 2.1.4). The capacity values vary even under the fixed flow rate values due to the different conditions. An influence of the various conditions was presented at chapter 2.1.5.

The second part of literature review discussed the evaluation methods for traffic algorithms. The detection rate and false-alarm rate were identified as useful algorithm quality measures (see chapter 2.2.1 and 2.2.2). Lacking evaluation methods for ATM control algorithm prompts the author to investigate the evaluation method for the traffic information system (the quality measures and possible errors are presented at chapters 2.2.3, 2.2.4 and 2.2.5) that will be further adapted for AIX-ProB. In general, the chapter 2.2 is a theoretical background for the evaluation methodology as is designed at chapter 4.

Finally, the third part of literature review (see chapter 2.3) put focus on a practical framework of the used algorithm. The author gradually presents traffic management strategies (see chapter 2.3.1), some typical systems used in Europe (see chapter 2.3.2) and finally a review of the European active speed reduction practice (see chapter 2.3.3) is obtained. Among others, the chapter points out the importance and shows some benefits of the highway traffic management systems.

3 DESCRIPTION OF THE USED MODEL TO DETERMINE TRAFFIC BREAKDOWNS

This chapter describes the fundamentals of AIX-Prob algorithm. In addition, some main features and advantages are put down to motivate a further evaluation.

The algorithm research was publically released by Schwietering (2010) as Ph.D. thesis that covers the whole development process.

3.1 ALGORITHM DATA FLOW

The algorithm principle is described using the data flow chart belowed (see Figure 14). The Event Calendar provides an input to the Logic Model concerning the information typically about a day period (weekday/weekend). In addition, the Environmental Data module delivers information about visibility and weather conditions (e.g. day or night, fog, rain). According to this entering data, the Logic Model processes the input and subsequently search for corresponding capacity distribution curves at Classified Curves of Probability of Breakdown.

With knowledge of the specific capacity distribution curve for the three time intervals (output of the Choice of relevant curve of Breakdown Interval element), for example algorithm may identify a curve for Monday, sunny conditions. With current traffic volumes in 1min, 5min and 15min aggregation, the Choice of Relevant Observation Interval module selects the worst (most risky) variant in order to ensure maximum reliability.

In the next step, the Event Based Traffic Pattern component generates a “factor of breakdown probability”. This factor determines a trend for immediately preceding flow rate using the collected data (generally, the Event Based Traffic Pattern delivers a flow rate pattern for the whole day). This feature is important regarding the “preventive nature” of the algorithm.

This value is compared with the Strategic Parameters. The Strategic Parameters specify the speed limits for the related breakdown probability. Considering a specific probability breakdown curve and “factor of breakdown probability”, the related speed restrictions are set. Obviously, the potentially more risky situations (higher probability of breakdown and lower factor of breakdown probability) are prevented by displaying the more restrictive speeds.

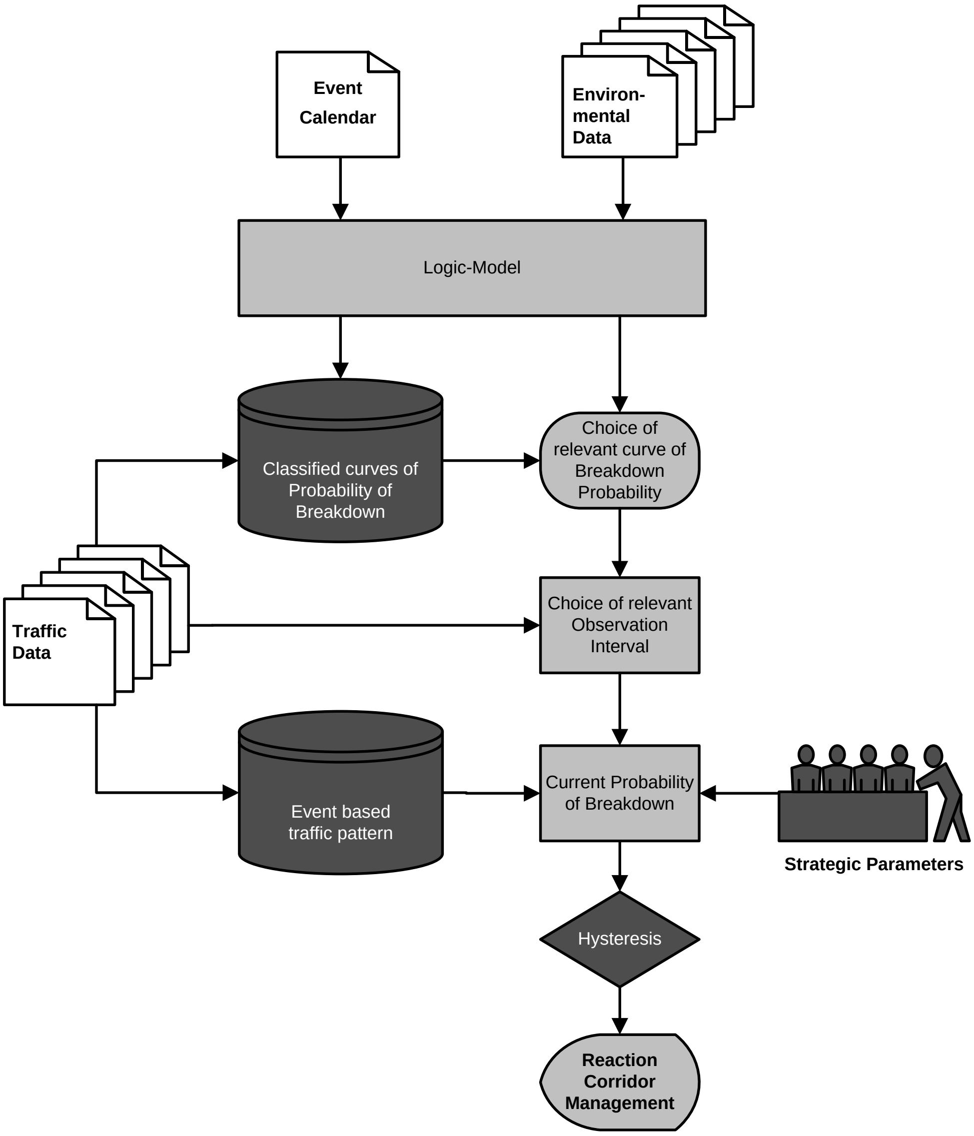

Figure 14: AIX-ProB data flow chart, source: Schwietering & Steinauer (2011)

Hypothetically, the certain level of the probability of breakdown is reached and the algorithm reflecting the Strategic Parameters and further increase of flow rate initiates a speed reduction. At this point, the Hysteresis module is employed and starts to count 5 minute interval. If there is no other capacity event occurred within this interval, the speed reduction is canceled. On the other hand, if there is another interval with the certain high level of the probability of breakdown within the 5 minute interval, an extension of the speed reduction is triggered or even it sets the more restrictive speed reduction if it is needed.

3.2 HIGHLIGHT OF THE ALGORITHM CAPABILITIES

The chapter 2.1.3 and 2.1.4 outline some advantages of the probabilistic approach over the traditional approach where capacity is determined by the fundamental diagram. The positive effects for ATM were summarized in chapter 2.3. Now, more detail discussion about the AIX-ProB algorithm as a dynamic speed reduction strategy is required to motivate further investigation. In this manner, the following conclusions comparing the AIX-ProB algorithm to the commonly used algorithms were introduced by Schwietering & Steinauer (2011):

- AIX-ProB considers the influencing conditions.

The new proposed algorithm is using an innovative approach considering a complex set of the conditions influencing capacity (see chapter 2.1.5). The AIX-ProB strategy does cover the weather conditions which directly determine visibility (as a crucial parameter affecting the driver behavior). Furthermore, the aspects like workday/weekend or commuter/recreational traffic are implemented. In contrast, the traditional algorithm of ATM are exclusively based on the traffic flow (or velocity), the newer ones sometimes complemented by the factors determining the weather conditions.

- Fast initial configuration and parameterization.

The author supposes that this is one of the most beneficial and the most innovative feature of the new algorithm. The traditional approach requires to adjust and to parameterize the single freeway sites, one by one (looking at the specific numbers of flow rate and speed in the k-q and q-v diagram), based on the collected data, experiences and knowledge of the road operator in order to achieve desired performance. Among others, this also means a time-consuming configuration and maintenance. Using the new proposed algorithm, the road operator just makes a decision about acceptable level of the breakdown probability. The policy maker can set low probability of the traffic breakdown, therefore formulate a restrictive system (e.g. following a safety incensement goal). An inverse decision is to accept the higher probability of the traffic breakdown and bring the system into a less-controlled regime.

- AIX-ProB is self-learning.

The self-learning is an attractive capability for the road operator that is promising "incessant" results improvement. At the end of every day, the data collected from the all highway sites where the speed reduction system is deployed are forwarded into the algorithm's database. The algorithm then utilize these data ("learning" them) in order to make the probabilities more accurate. Remind that probabilities are computed as a ratio between the intervals exceeding the traffic breakdown and the total number of the measured interval (see chapter 2.1.4). It appears that more available data give better precision in the traffic breakdown occurrence determination (probability theory fundamental - the more available attempts obtain the better results of an experiment).

- AIX-ProB deploys Probabilistic approach.

The chapter 2.1.3 discusses some limitations of the traditional approach of determining the capacity. If one requires the real image about the actual capacity situation on the highway, the fundamental diagram used by the commonly deployed algorithms is insufficient. AIX-Prob is using the innovative probabilistic approach to overcome these limitations.

- Preventive nature of the algorithm

So-called "preventive nature" of AIX-ProB determines the operational area of the algorithm. Taking into account sufficient ratio between detection rate and false-alarm rate, the algorithm anticipates the traffic breakdown with 5 minutes advance.

4 METHODS FOR THE TRAFFIC BREAKDOWN PREDICTING ALGORITHM EVALUATION

The purpose of the evaluation developed in this master thesis is to confirm the AIX-ProB algorithm's suitability for the Austrian highway network, taking into account the intended objectives. The suitability is determined by metrics used in a specific evaluation method (see chapter 4.4) and intended objectives are summarized into stakeholder aspirations (see chapter 4.2).

The most effective and conclusive way of the algorithm evaluation is to take the data obtained before any traffic lane management (dynamic speed reduction) is deployed (so-called uncontrolled data) and compare it with data produced after the investigated system is implemented. This straightforward evaluation was presented for example in Rose & Ullman (2003) and Stoelhorst et al. (2011). Unfortunately, the author does not have access to the uncontrolled data and therefore the universal evaluation methods (obtaining the results regardless the data before the control system implementation) are necessary to develop and use.

4.1 ROAD MAP

As was stated in the chapter 2.2 there are no available evaluation guidelines for the traffic breakdown predicting algorithms or even for their application as a “module” for the preventive traffic control systems. Thus the systematical approach illustrated in the form of “road map” is employed in order to develop the evaluation criteria (see Figure 15). The road map describes the motivations and intentions of the algorithm evaluation.

Aiming to do the evaluation methods determination, Chapter 4 follows the road map stated above. The methods description (see chapter 4.4) is reduced to the set of methods which are feasible for analysis within the parameters of this thesis. However, a complete umbrella of the need-method relations is included and outlined in chapter 4.2.

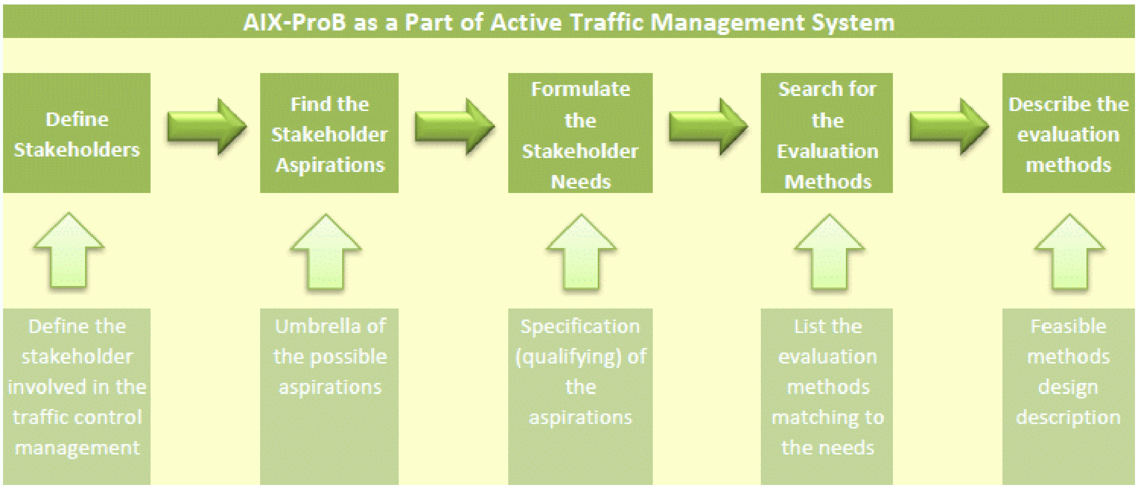

Figure 15: Road map employed for the evaluation methods development

4.2 STAKEHOLDERS AND THEIR ASPIRATIONS

The following traffic management system stakeholders were defined:

- Drivers.
- National/regional road operators (e.g. Asfinag).
- Traffic management system contractors (e.g. Heusch-Boesefeldt).
- Traffic national/regional policy makers (e.g. Ministry of transport).

Once the stakeholder participating groups were found, their particular interests might be understood in relation to investigation (see Table 4).

Understanding the specific stakeholder needs appreciably helps to clearly define the requirements which are reflected by a set of the desired evaluation procedures. In other words, whereas the drivers group is interested in (for example) travel times, the road operator group is concerned with impact of the management system of traffic flow. Such criteria should be considered in the evaluation methods. The initial set of the stakeholder aspirations and needs was discussed with ASFINAG and additionally adjusted based on their desired objectives.

Table 4: Stakeholders, Aspirations and Needs for traffic predicting breakdown algorithm

Stakeholders	Aspirations	Needs
Drivers	Get from point A to B in the shortest possible time	N1
	Do not get stuck in the congestion	N2
	Reducing the number of traffic breakdowns in order to make the ride smooth (especially for truck drivers)	N3, N4
	The speed restrictions represent current traffic situation	N4, N5, N6, N7, N11, N12
	Get safely from point A to B	N2, N3, N4, N6, N8, N11, N16
National/regional road operators	Make traffic smooth	N2, N3, N4, N5, N6, N8
	Avoid senseless traffic regulation	N4, N5, N6
	High level of trustworthiness, driver acceptance	N5, N6, N12
	The algorithm is applicable on the all controlled highways	N7
	Smooth traffic flow even in unfavorable conditions	N3, N8
	Drivers will promptly follow the restrictions	N6, N9
	The control system action comes with minimal delay after the event indication	N10
	The algorithm is able to detect all possible capacity events	N11
	Improve traffic safety	N2, N3, N4, N6, N8, N11, N14, N16
	Improve the attractiveness of the highways for trucks offering smooth driving conditions	N1, N2, N15
Traffic national/regional policy makers	Support the particular goals of the road operators	linked to the road operator needs
	Financial benefit	N13, N14

Need id	Stakeholder needs
N1	Short travel times
N2	Traffic flow harmonization
N3	Minimize congestion
N4	Display the speed limits with sufficient time margin
N5	Cancelling the speed limit displaying immediately after the capacity event termination
N6	Display the speed limits appropriate for the traffic situation (regarding the controlling logic and consider the spatial and time accuracy)
N7	Algorithm robustness

Need id	Stakeholder needs
N8	Speed reduction reflects the given spatial, weather and daytime conditions
N9	Effectiveness of the undertaken control actions
N10	Minimal processing time consider the algorithm performance, information perception and distribution
N11	High detection rate
N12	Minimal false alarm rate
N13	Reasonable return of investment
N14	Minimizing the externality cost
N15	Maximize toll collection
N16	Improve safety
N17	Information about availability of the road network

In total, 17 possible aspirations and 17 stakeholder needs have been determined. Note that Table 4 covers drivers, road operators and traffic policy as potential interest areas of solution developers. Additionally, the definition above assumes algorithm installation into a comprehensive traffic control system employed on a regional or national freeway network. It appears that the satisfaction of stakeholder aspirations requires relatively wide scope of the needs; it covers the issues of from the algorithm's operability, through the needs of improving roadway safety impact, up to the maximum algorithm's quality.

4.3 Search for the Evaluation Methods

In general, a qualitative analysis of stakeholder needs helps the researchers to find appropriate evaluation methods. The evaluation methods should plainly facilitate measurements of the fulfillment of stakeholders' aspirations. It appears that an acceptable evaluation method must produce clearly interpretable results.

Besides a lack of literature and theoretical recommendations (guidelines), the following possible obstacles must also be taken into account:

- Available data

  For example, which kind of data is available, quality, consistency, completeness, source and desired precision.

- Time constraints
- If there is limited time to obtain such an evaluation, one must determine the most

effective way to conduct an evaluation. Alternatively, the scope of the evaluation has to be reduced.

- Method complexity

  For example: consider the computation expensiveness.

- Method product

  Assure through analysis that the methods produce the demanded results.

Substantiating the extent of the stakeholders' needs (see Table 4) naturally requires more comprehensive and extensive evaluating methods. Within the framework of this master thesis, the author is limited by time constraints and the complexity of some methods (especially regarding sociological and economical aspects).

However, the brief discussion over the set of stakeholder needs and related evaluation methods is necessary. This is demonstrated in the table below (see Table 5).

Table 5: Relation between the evaluation methods and the stakeholder needs

Need id	Stakeholder needs	Evaluation methods
N1	Short travel times	M3
N2	Traffic flow harmonization	M1, M2
N3	Minimize the congestion	M1
N4	Display the speed limits with sufficient time margin	M1
N5	Cancelling the speed limit displaying immediately after the capacity event termination	M1
N6	Display the speed limits corresponding to the traffic situation (taking into consideration the controlling logic and consider the spatial and time accuracy)	M2
N7	Algorithm robustness	M1
N8	Speed reduction reflects the given spatial, weather and daytime conditions	M1
N9	Effectiveness of undertaken control actions	M4
N10	Minimal processing time considering the algorithm performance, information perception and distribution	M5
N11	High detection rate	M6
N12	Minimal false alarm rate	M7
N13	Reasonable return of investment	M8
N14	Minimizing external costs	M8
N15	Maximizing toll collection	M8

Need id	Stakeholder needs	Evaluation methods
N16	Improve safety	M10
N17	Information about availability of the road network	M1

Method id	Assessment method
M1	STSF analysis
M2	Speed-time analysis
M3	Travel time-time analysis
M4	Speed-distance analysis regarding the specific combination of detector and VMS, consider the drivers behavior
M5	Time analysis of the control system, tracking the process: detector - TCC - VMS
M6	Detection rate analysis
M7	False-Alarm rate analysis
M8	Financial analysis
M9	Flow rate prediction analysis (analysis in terms of prediction quality)
M10	Investigation of the amount of dangerously low-headways consider the vehicle speed

Legend	
	Intended methods for the evaluation
	Out of a master thesis project range

The methods M1-3, M6, M7 and M9 are described (and their relation to the stakeholder needs) in chapter 4.4. Note that the widely discussed need N7, e.g. Brilon & Geistefeldt (2009) calls for an evaluation method applied to the bulk data and subsequently assess the demanded criteria. In this manner it is intended to prove the algorithm's benefit by subordinating the data sample to the Space-Time Speed Field (STSF) analysis. This analysis investigates the algorithm performance with respect to the different (weather and roadway) conditions.

The method M4 analysis driver's behavior when he or she passes the gate with a speed reduction. There are several aspects to observe, for example:

- Distance (downstream or upstream) where the driver starts to adapt the vehicle speed.
- How strong is a single vehicle speed reduction?

This measure has a value in the traffic management effectiveness analysis. The evaluation is indeed strongly influenced by the drivers' behavior and other sociological aspects. Some findings are published at Steinhoff et al. (2002).

The method M5 investigates information flow over a communication channel: detectors – TCC – actuators. The potential delays might cause (among others) inconsistencies in the dynamic speed reduction management and significantly affect the system's operability.

The method M8 is a classic topic of transportation economy and management science. Naturally such an analysis might be considerably extensive, and reveals a number of aspects, for example:

- Investment intention (calculate the return of investment).
- System's operation cost.
- System's impact and society benefit (calculate the external cost).

4.4 Evaluation Method Description

The following chapter presents the evaluation methods design. The number of presented methods is restricted by the limited complexity of the master thesis. Thus, the author chose the methods evaluating the algorithm correctness (the detection and false rate) and performance (travel time analysis).

The table below (see Table 6) briefly presents the applied evaluation methods, including their main principles, features, limitations and outputs. A detailed description is further explained in the related sub-chapters.

Table 6: Evaluation methods summary

Evaluation Method	Evaluation Objectives	Principle	SW Tools	Used Data	Benefit	Limitations & Difficulties	Implication
Traffic Breakdown Recognition Analysis	Traffic breakdown recognition accuracy	Investigate the speed characteristics, investigate the incidents and compare them to algorithm's recognition outputs	MS Excel	Passenger car velocity, flow rate, algorithm's recognition output	Evaluated recognition ability and subsequently its quality	Precise traffic breakdown recognition requires highly individual investigation of all incidents	Evaluate algorithm foundation. The quality breakdown recognition is a prerequisite for further successful algorithm employment.
STSF Analysis	Time relevance	Investigates correctness of the control interventions regarding time extent	MS Excel, Matlab	Passenger car velocity, Speed reduction control, Traffic congestion occurrence	Well arranged graphical interpretation, possible numerical evaluation, STSF can be also used for another evaluation or observations, reveal a concrete error source	Determine the relevant time margins ΔT_1, ΔT_2	Algorithm quality quantification (time relevance of speed reduction), determine algorithm
	Spatial relevance	Investigates correctness of the control interventions regarding spatial extent				Determine the relevant distance margin ΔL_1, ΔL_2	Algorithm quality quantification (spatial relevance of speed reduction), determine algorithm
	Control mismatch	Computes a number of unreasonable speed restrictions				Available data, Determine the resolution power	Determine algorithm quality regarding the mismatches
	Control missing	Identifies the congestions without uncovered by the control restrictions				Not identified yet	Determine the fatal error of missing speed reduction
False-Alarm rate	Determine number of wrong speed reduction with respect to overall control effort	What percentage of speed control is displayed outside the congestion-relevant area/time window	MS Excel	Passenger car velocity, Speed reduction control, Traffic congestion occurrence	It is possible to differentiate between traffic breakdown severity	Do not distinguish between type of error, determine an area of the preventive potential (extension of area C)	Evaluate algorithm correctness
Detection rate	Quality of prediction	What percentage of congestion is covered by the speed control					Determine the algorithm preventive effect

4.4.1 SPACE-TIME SPEED FIELD (STSF) ANALYSIS

This method utilizes the technique described in 2.2.2, 2.2.3 and partly in 2.2.1. First, this approach obtains an intuitive description of traffic situation using the STSF plot, the same which was used for example by Bogenberger (2004) and Bertini et al. (2005). Among others, this is beneficial in situations when the capacity events (or any other of unusual situations) have occurred. Second, introducing the evaluating indexes provides an opportunity to establish a robust tool with the capability to assess the algorithm performance taking into consideration number of the aspects. This property needs some extensions of the method as was presented at 2.2.2, 2.2.3 and 2.2.5. The extension represents a “control effort” of the algorithm. There are no guides available publicly regarding how to introduce such a feature into the STSF. It is intended to stick up to the pattern fashion where the control interventions are displayed as the polygons with the corresponding spatial and time dimension.

An example of possible STSF characteristic is sketched in **Figure 16**. The figure shows basic STSF analysis that describes the current velocity (numerical interpolation is applied) with respect to the investigated section (x-axis) over observed time (y-axis). The blue line polygons represent the interventions made by the VSL. Note that power of the reductions is classified by the line color.

4.4.2 STSF CRITERIA

The number of criteria is developed in order to investigate possible error situations that might occur using the dynamic speed reduction system. In principle, the author has available the three bulk input samples:

- Speed data

  The speed data contains information about actual vehicle speed collected by the loop detectors with respect to time and spatial extent.

- Control data

  The speed data presents set speed regulations (100, 80, 60 and 30 km/h) with respect to time and spatial extent.

- Jam data

The jam data points out traffic breakdowns and following congestion incidents with respect to time and spatial extent.

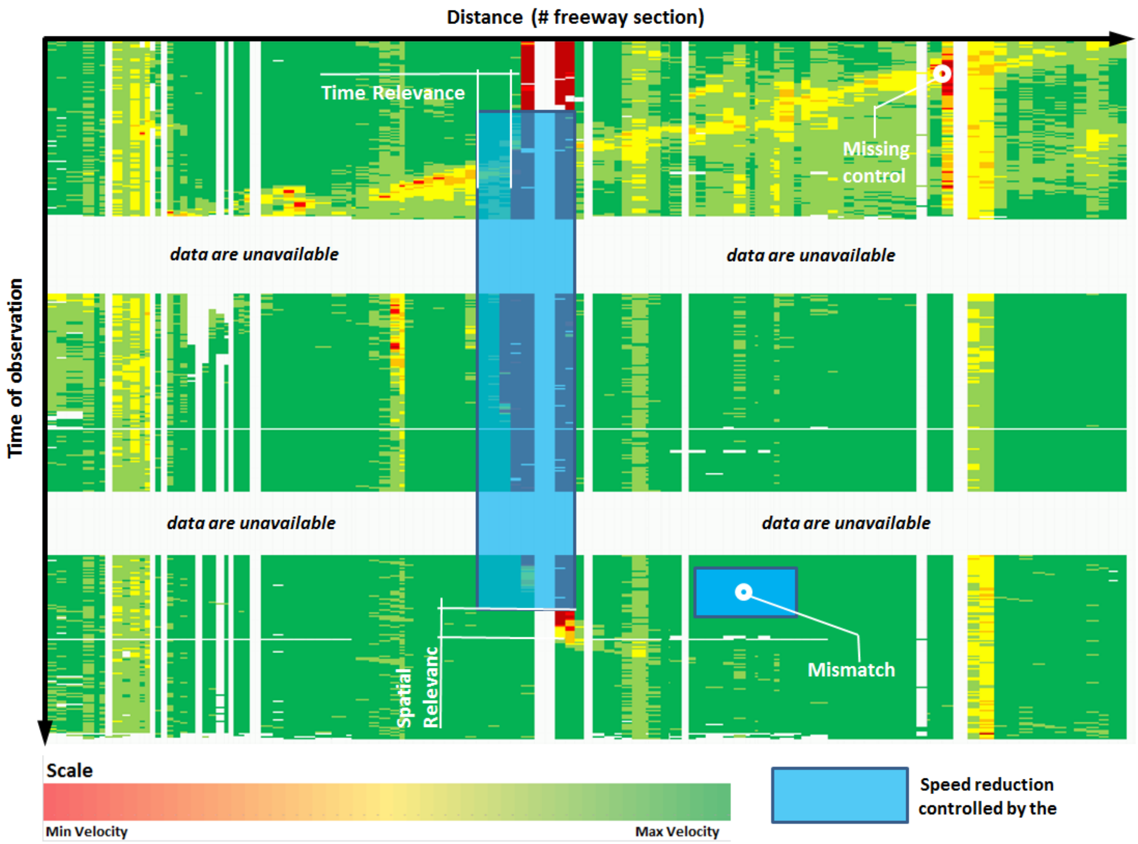

Figure 16: Sketch of a STSF example

4.4.2.1 Speed Reduction Time-Relevance Criterion

Similar to the approach presented 2.2.5, the speed reduction time-relevance criterion is introduced (see **Figure 16**). The criterion evaluates if the speed reduction was displayed with sufficient time margin before an incident occurs and how long it stays displayed after the incident has disappeared; it investigates if the vehicles are subordinate to over-regulation. For this purpose the traffic breakdown cases are investigated. The traffic breakdown initiation has to be prevented by the displaying the speed limit with a sufficient time limit. It guarantees the sufficient time margin for drivers to adapt the vehicle speed. On the other hand, it is intended to not over-regulated traffic flow when the traffic flow is restored. Thus, the speed reduction should disappear after the vehicles again reach their desired speed (that is equal to the free flow speed). To evaluate the sufficient time limits, the quality levels considering the specific time intervals before and after the bottleneck are described in Table 7.

Table 7: Quality levels for Speed Reduction Time-Relevance Criterion

Speed Reduction Time-Relevance			
Quality levels		Time margin ΔT_1 [min][1]	Time margin ΔT_2 [min][2]
Labeled scale	Numbered scale		
Excellent	3	5:00 - 3:01	0:00 - 2:00
Fair	2	3:00-1:01	2:01 - 3:00
Poor	1	> 5:01, < 1:00	> 3:01

[1] ΔT_1 is time margin directly preceding the bottleneck
[2] ΔT_2 is time margin successive the bottleneck

The flow chart below (see Figure 17) shows the developed criterion's design that employs the predefined quality levels. Note that the results are differed into the three quality levels with respect to a control within the interval ΔT_1 preceding a jam and a control within the interval ΔT_2 directly follows a jam. The original code used for the evaluation is presented at Appendix A.

4.4.2.2 Speed Reduction Spatial-Relevance Criterion

Once the time relevance is evaluated, the spatial relevance is necessary to evaluate as well. Note the findings from Bogenberger presented in chapter 2.2.5. It is intended to calculate if there is sufficient spatial (distance) margin in front and after the congestion.

A selection of suitable spatial margin is not a trivial task. For example, the distance between the gantries has to be reflected. In principle, there are national standards for the allocating the gantries, however these values could vary over the spatial characteristics. Moreover, the AIX-ProB restricts the speed on 100km/h, 80 km/h and 60km/h. In contrast to the first two reductions which can be displayed without any previous control, the 60 km/h reduction requires at least one 80 km/h or 100 km/h speed restriction to be displayed before.

The author chose the following measures for spatial relevance criterion (see Table 8). The number of preceding/successive gantries is stated with respect to the value of speed restriction. The parameters respect the fact that on German and Austrian highways (where the data obtained by AIX-ProB trial are available) is a typically distance between two gantries equal 2 km. The spatial relevance analysis assumes that the control consistency is observed (this is controlled by a superior "control component" in the traffic control center).

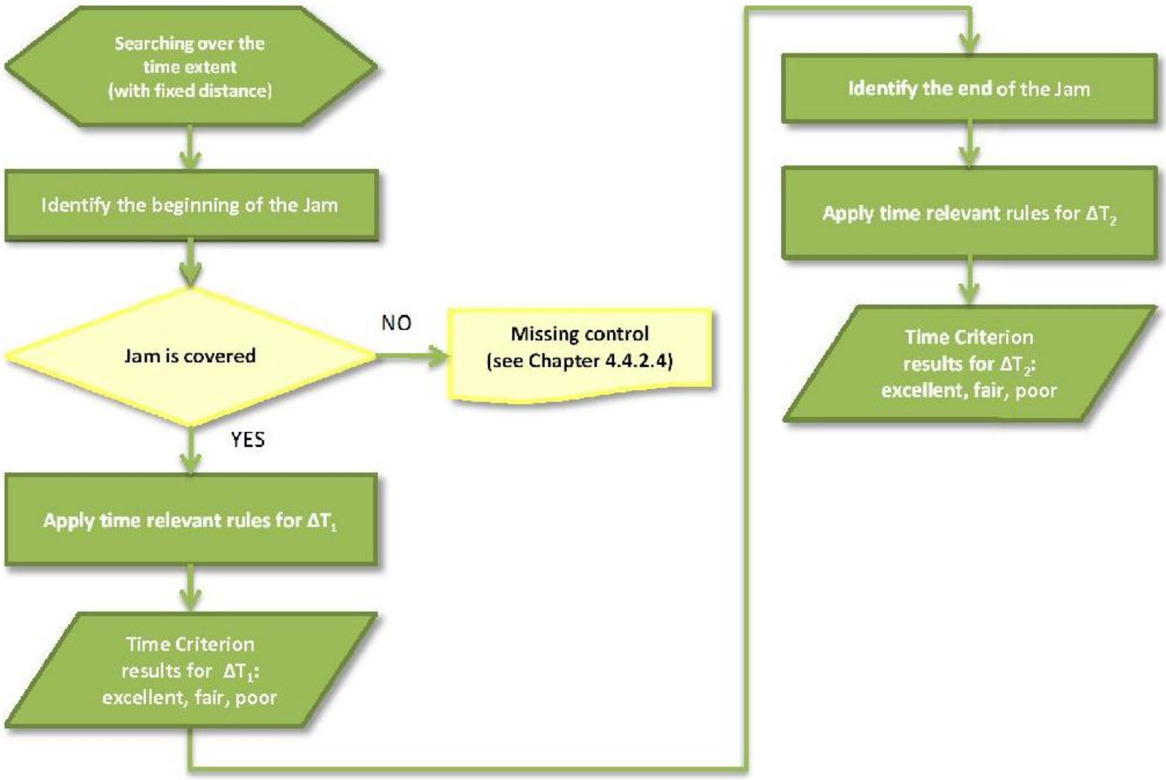

Figure 17: Speed reduction time-relevance criterion's design

Table 8: Measures for Speed Reduction Spatial-Relevance Criterion

	Speed Reduction Spatial-Relevance					
	ΔD_1 [gates][1]			ΔD_2 [gates][2]		
	Speed reduction			Speed reduction		
	100 km/h	80 km/h	60 km/h	100 km/h	80 km/h	60 km/h
Acceptable	0	0 ÷ 1	1	0	0	0

[1] ΔD_1 is equal to distance preceding the bottleneck

[2] ΔD_2 is equal to distance successive the bottleneck

The flow chart below shows the developed criterion's design. Note that the evaluation algorithm assumes the control consistency. The original code used for the evaluation is presented at Appendix A.

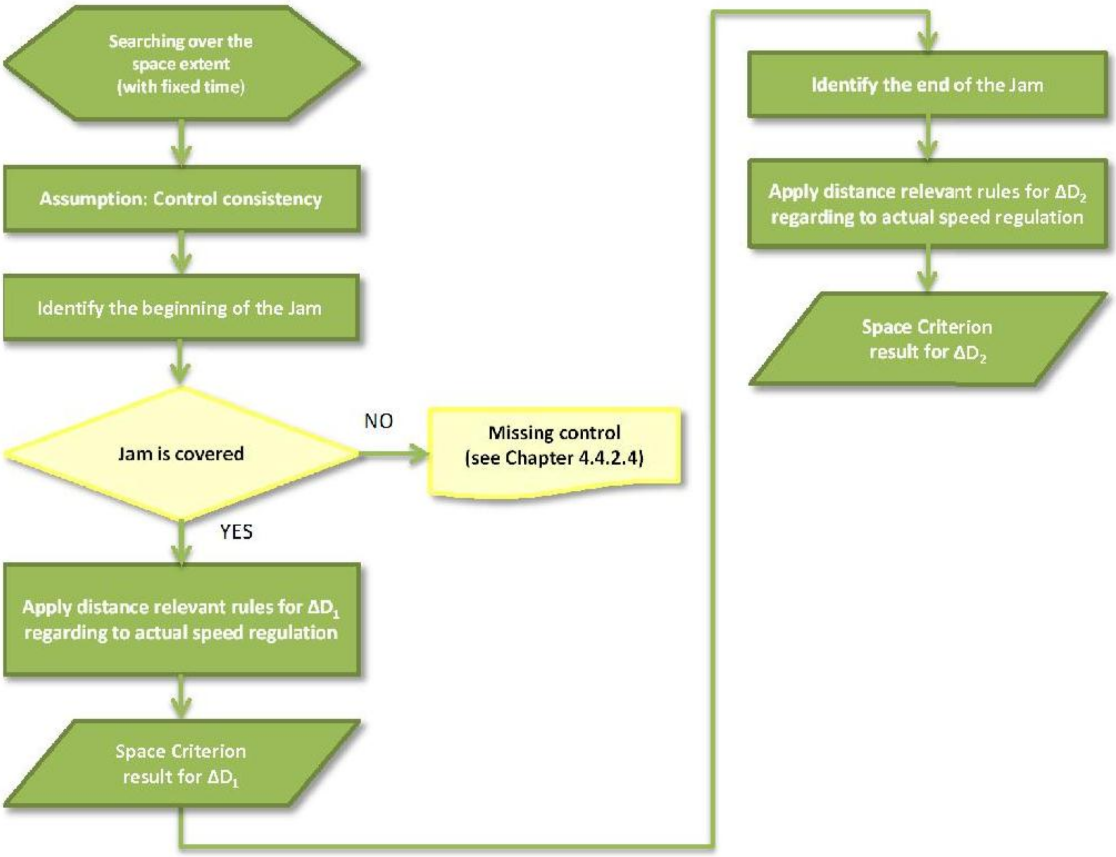

Figure 18: Speed reduction spatial-relevance criterion's design

4.4.2.3 CONTROL MISMATCH CRITERION

The criterion aims on a severe situation when the algorithm displays the speed reduction with no reason of the present or future traffic conditions. This unreasonable restriction influences the system trustworthiness and therefore it affects the system operability.

To evaluate the mismatch criterion all the "isolated" speed reduction (see **Figure 16**) actions have to be identified. An example below illustrates the most "negative" situation where a presence of the speed reduction is absolutely wrong since all the close vicinity of control pattern is clearly green (vehicle desired speed). Recalling a preventive nature of AIX-ProB algorithm (and its function in lane management system), there might be another example where an action appears at green area but in close vicinity are speeds implying potential congestion event occurrence. In such a scenario, the speed reduction is actually needed.

There are two methods how to cope with this problem. First method would be to firstly investigate non-controlled data. The data sample collected during the reasonably long period along the freeway where the speed reduction management is not deployed. Afterwards, apply the controlled data and compare the same freeway sites. The author has not available such a kind of data.

Thus, the author developed an alternative method. It assumes that all kind of mismatches cannot be detected (regarding the available data). Nevertheless, the most severe mismatches might be recognized if some quality measure is introduced. The quality measure here determines an extent of "close vicinity" where the potentially dangerous speed values are located. The close vicinity is described as 5 and less minute interval before the speed reduction initiation and the distance of 3 and less detection loops from the place of the speed reduction initiation. At the same time, only vehicle speeds equal to 80 km/h and less are considered as relevantly implying a further congestion event. The determination of so-called "resolution power" (5 minutes, 3 gates and 80 km/h) is a sticking point of the mismatch evaluation. Table 9 shows the intended evaluation metrics. It appears that using such a method, the desired preventive capability of the algorithm is considered as an error. The author assumes that the AIX-ProB as an algorithm with a strong preventive character is going to be partly handicapped (compare to the algorithms with a lack of the anticipation abilities) and this aspect has to be reflected against the obtained results.

Table 9: Mismatch evaluation metrics

Control Mismatch[1]			
Quality levels		Total operations / Total mismatches	a/b
Labeled scale	Numbered scale	Mismatches [%]	
Excellent	3	100 - 85,1	
Fair	2	85 - 70,1	
Poor	1	< 70	

1 - Intended resolution power:
…dangerous speeds < 80 km/h
…relevant distance < 6 gates
…relevant time < 5 mins

The author used the macro coded with MS Excel VBA to carry out the mismatch evaluation over the bulk data. First, the code searches over the data and reveals the intervals (with respect to time and spatial extent) where speed reduction is employed and at the same time no traffic congestion is detected. Such an incident is marked as suspicious and its close vicinity (as was defined by the resolution power) is further investigated to reveal if it is a real mismatch or not. The code is presented at Appendix A.

4.4.2.4 CONTROL MISSING CRITERION

This is the reverse criterion to the previous mismatch control error. In this case, the traffic breakdown has occurred and no control intervention is realized (see **Figure 16**). Naturally, this type of error is considered as grave and it is significantly involving in the algorithm quality.

The control missing evaluation code seeks for the intervals where the traffic jam is presented and it is not roofed by the speed reduction. These incidents are labeled as control missing errors. The complete VBA code can be found at Appendix A.

4.4.3 DETECTION AND FALSE-ALARM RATE USING THE STSF ANALYSIS

It appears that the detection and false-alarm rate are the two fundamental measures determining the algorithm quality and subsequently its operability. False-alarm rate is solid method to determine the algorithm correctness. Detection rate determines the algorithm prediction quality.

Since the traffic situation and related control interventions are described by the STSF analysis, the detection and false alarm rate may be evaluated using a technique similar to one showed at 2.2.3.

The design of the detection and false-alarm rate analysis (based on the STSF) is showed on the figure below (see Figure 19). As one can see the congestion area C is extended on C'. The extension has two reasons:

- Extension of the congestion area to the "past" ($-\Delta T_1$, $-\Delta L_1$) reflects preventive nature of the algorithm.
- Extension of the congestion area to the "future" ($+\Delta T_2$, $+\Delta L_2$) represents a need to prevent an over-regulation effect of the algorithm.

Note that the values ΔT_1, ΔT_2 are chosen like 5 minutes, 2 minutes time intervals respectively. Thus it reflects high demands in the manner of a definition stated at chapter 4.4.2.1.

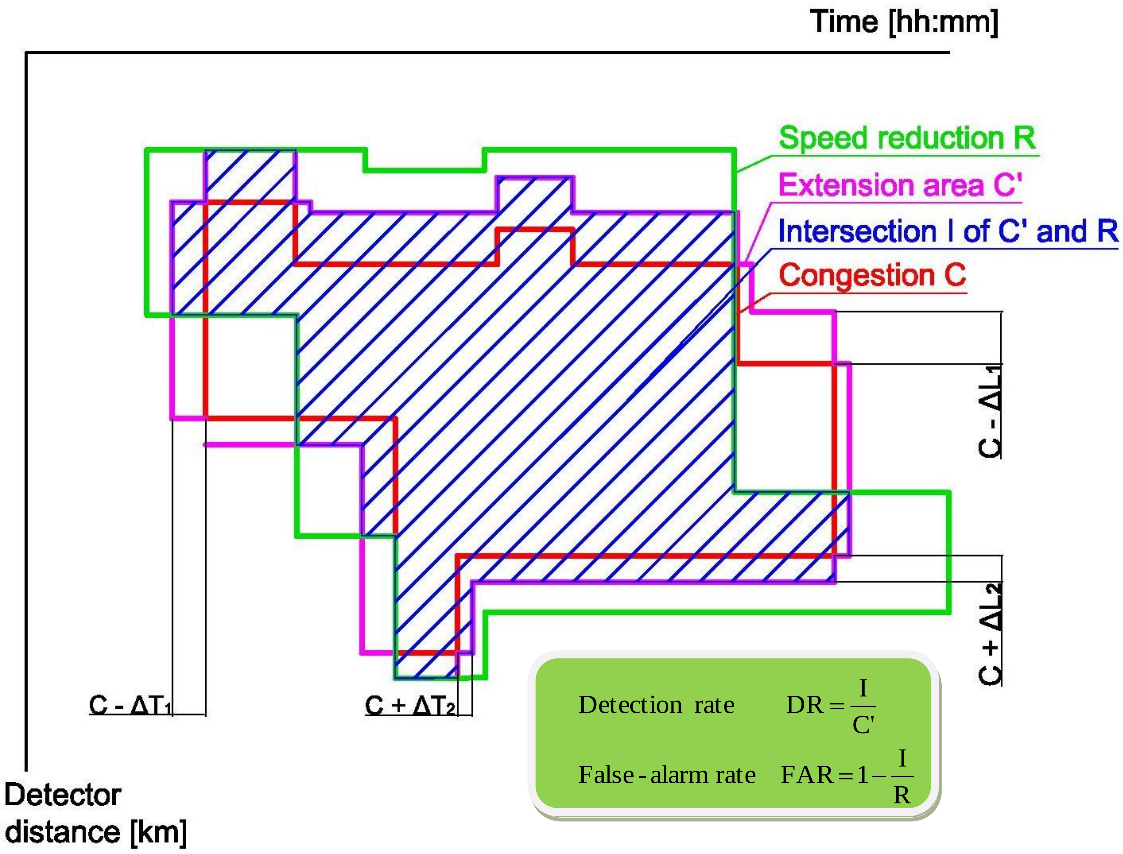

Figure 19: Design of the detection and false-alarm rate analysis (based on the STSF)

The evaluation code is derived from the method design at Figure 19. First, it computes the areas for C, C’, R and the intersection I; the computed area sizes are afterwards substitute into the formulas for detection and false-alarm rate. Similarly to this approach, the author determines the rates for specific speed reductions values. In this case, it is distinguished between the R areas for 100, 80 and 60 km/h. The VBA macro is presented in Appendix A.

It appears that result interpretation following the previous method design can be problematical. Specifically, the method delivers corresponding results for the detection and false alarm rate in a range between 0 and 1 (0% to 100%), however, it does not reflect capacity incident severity. The author supposes that the relevant result values should say if FAR equals to 90 % is belonging to 5 minute congestion on a freeway section of 2 km, or if it is belonging to a several hours’ congestion taking place along the majority of an observed freeway section (in this case 90% represents very poor speed reduction performance). Therefore, it is intended to introduce a set of weights that allows ranking the results according to the congestion size.

4.4.4 TRAFFIC BREAKDOWN RECOGNITION

Regarding to the findings from the literature overview (see chapter 2.1.4), successful employment of the capacity stochastic approach is based on accurate traffic breakdown determination. Thus a necessary prerequisite for a further evaluation is to find out whether the algorithm's input values of traffic breakdowns were correctly identified.

The author decided to evaluate traffic breakdown recognition in two steps:

1. Quality of traffic breakdown recognition

In the first step, it is intended to take into account the traffic breakdown incidents as were identified by the algorithm (the method assumes that the breakdown incidents were identified correctly). Then, it evaluated if the moment (interval) identified by the algorithm as traffic breakdown is correct or not with respect to previous/following velocity values.

The output of the first step determines the quality of traffic breakdown recognition. In the other words, how accurately are the traffic breakdowns recognized. Besides that, the image about typical velocity performance (the speed drops) is provided.

2. Algorithm's ability to recognize breakdown

The first step declares a strong assumption that the all incidents recognized by the algorithm are the traffic breakdowns (correct recognition). Naturally, it has to be evaluated if the algorithm recognizes all traffic breakdowns which have occurred in the observed data sample and on the other hand, if the algorithm marked some false traffic breakdowns. However, this is not a trivial task because it has to be decided what actually determines the traffic breakdowns and congested traffic conditions. Therefore, the author introduced the following set of parameters which characterize congested conditions and then compare if these incidents are matching with the traffic breakdowns recognized by an algorithm.

- Speed Drop SD

  Speed drop determines the severity of traffic breakdown. It appears that if one selects a higher value for a speed drop is set, the more severe traffic breakdowns are taken into account.

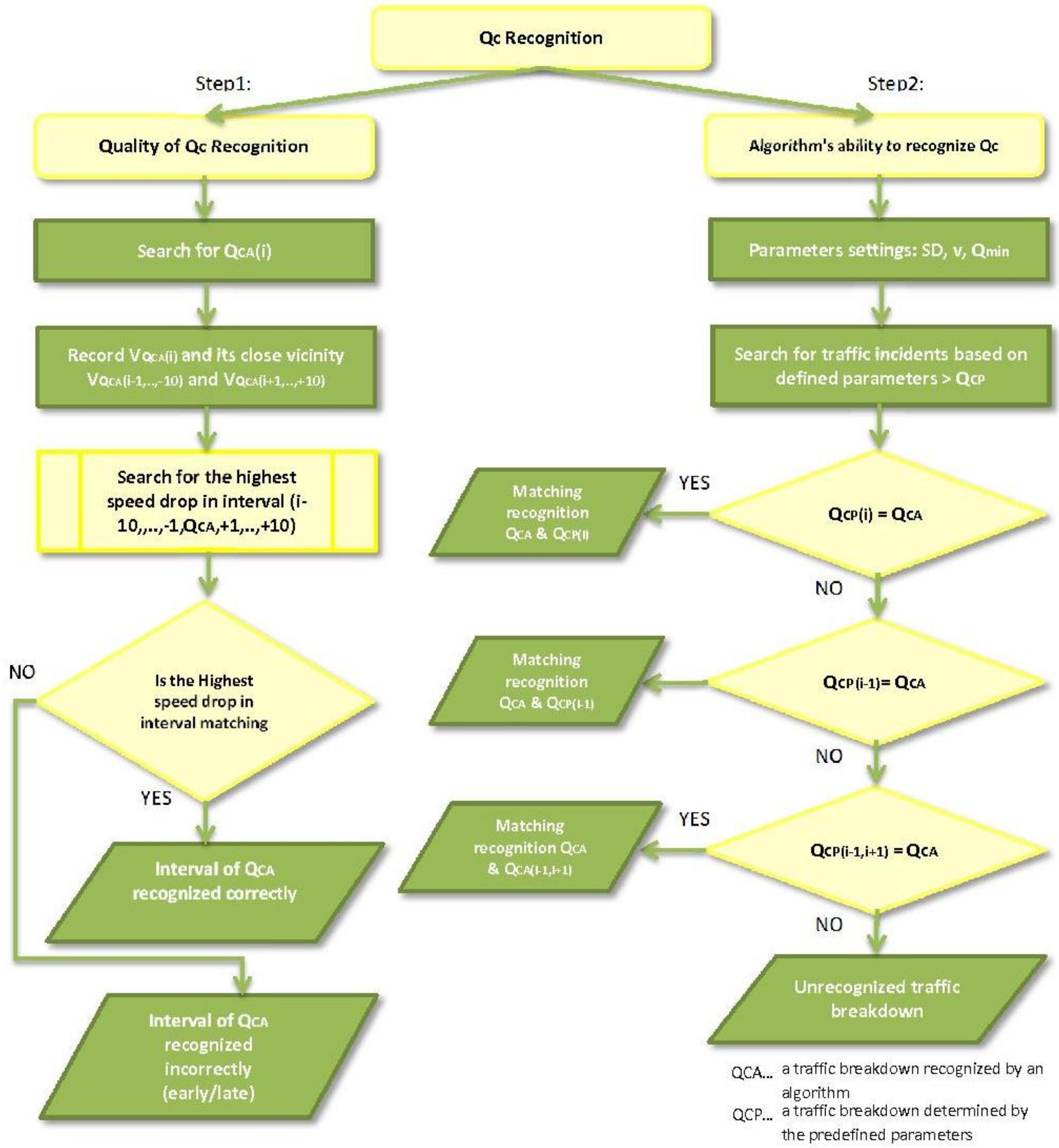

Figure 20: Traffic Breakdown Q_C Recognition Evaluation Method Design

- Actual speed v

For example, if there is speed drop from 130 to 115 km/h (within one minute interval) it is not intended to select such an incident as speed drop since the speed values are still relatively high and thus speed reductions are not required.

- Flow rate Qmin

  Flow rate is used as help indicator. For example during the night, the number of vehicles which are passing at the given section over the measured interval is rather small. Thus, the speed values strongly vary same as vary the velocity of single vehicle speed; there the flow rate is under the defined threshold value Qmin. It is intended to filter out the situations when the speed drops between the subsequent time intervals does not represent any capacity incidents.

The parameters setting in the step 2 can be considered as a critical point. It provides solid method how to carry out the evaluation over the bulk data; however the evaluation stands on the accurate parameters setting. The author therefore obtained the manual traffic breakdown recognition as well. This approach is convenient since the traffic data has strong stochastic nature; on the other hand it is not sufficient for large amount of data. The overall concept of the traffic breakdown recognition evaluation method is showed at the flow chart below (see Figure 20).

5 EVALUATION

5.1 TRAFFIC BREAKDOWN RECOGNITION EVALUATION

As an example, one detector at the Austrian freeway network was randomly chosen and its data acquired within twelve month period (1.1. - 31.12. 2007) was used. The data sample contains speed and flow rate values measured with one minute period, additionally the traffic breakdown recognition values delivered by three different strategies:

- “Brilon&Geistefeldt”: A strategy derived from method presented at Brilon & Geistefeldt (2009).
- “OldAIX-ProB”: An initially employed traffic breakdown recognition strategy.
- “AIX-ProB”: A currently used traffic breakdown recognition strategy.

5.1.1 QUALITY OF TRAFFIC BREAKDOWN RECOGNITION

The MS Excel VBA procedure was employed to carry out the evaluation as was designed at 4.4.4 (see left branch at the flow chart presented at Figure 20). Note that in the quality of traffic breakdown recognition evaluation, the highest speed drop observed within the 21 time interval data sample (interval for traffic breakdown plus ten preceding and ten following intervals) that is marked by an algorithm as traffic breakdown is considered as “correct” algorithm’s recognition.

Totally it was discovered the 1111 traffic breakdowns identified by the Brilon&Geistefeldt, the 129 traffic breakdowns for the OldAIX-ProB and the 1305 traffic breakdowns for the Aix-ProB. The histogram (see Figure 21) reveals several important findings. The OldAIX-Prob strategy correctly determined the traffic breakdown interval in the 105 cases (81%). The term “correctly determined” points out the fact that the interval with the most frequent occurrence the highest speed drop is the time interval number 11, the interval marked by the algorithm as the traffic breakdown. However the strategy revealed only the most severe breakdowns (number of identified breakdowns is significantly lowered compared to other strategies). The Brillon&Geistefeldt strategy performed the traffic breakdown detection correctly in 590 cases (53%). In the 53% of all cases (that is equal to 707) AIX-ProB correctly found the traffic breakdown. It can be observed that whereas Brilon&Geistefeldt tends to rather late recognition (see the yellow column with 123 incidents for time interval 10).

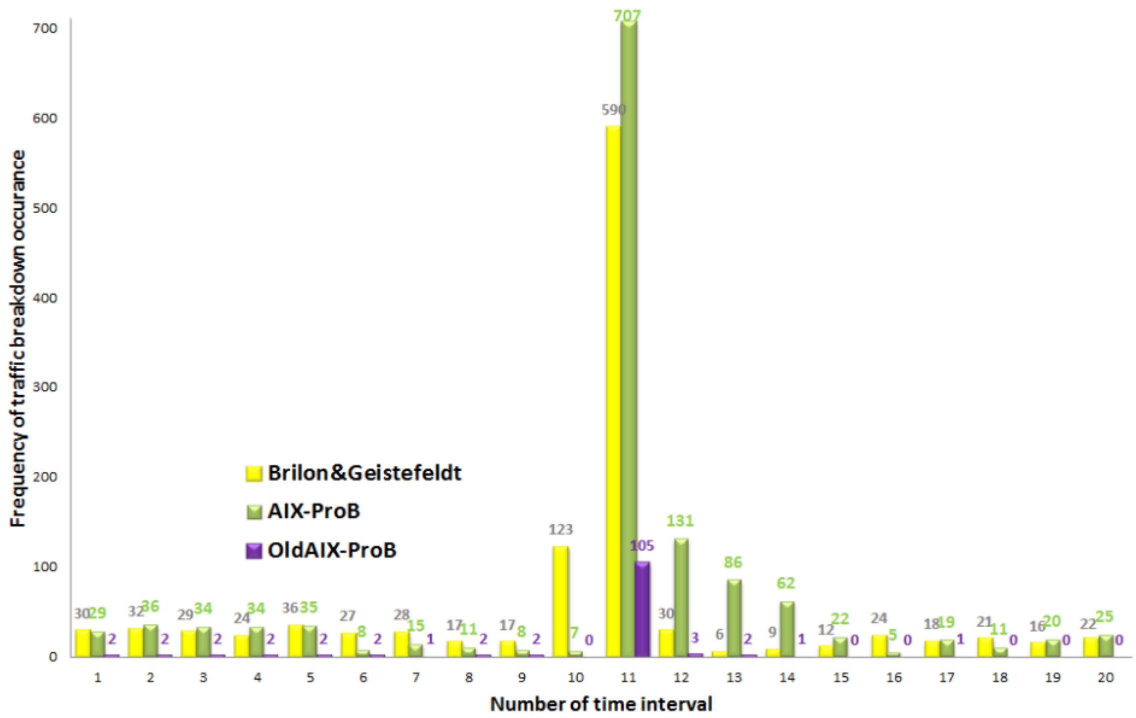

Figure 21: Traffic Breakdown Occurrence Histogram

The previous analysis determines the quality of traffic breakdown recognition in matter of the highest speed drop. Additionally, the average (considering all the detected incidents by a specific algorithm) speed curves were plotted (see Figure 22). It confirmed a previous statement that the Brilon&Geistefeldt strategy is tending to late recognition (see that for the yellow curve, the drops comes at the 10th time period). The OldAIX-ProB average speed curve represents an “ideal” example of traffic breakdown recognition. This corresponds also to a previous finding that the strategy aims only on the most severe breakdowns. The traffic breakdown recognition performance for AIX-ProB can be considered as acceptable since the significant drop is appearing after the recognized traffic breakdown (time interval 11).

5.1.2 Traffic Breakdown Recognition Ability

This sub-chapter obtains traffic breakdown recognition ability evaluation following the method design presented at 4.4.4.

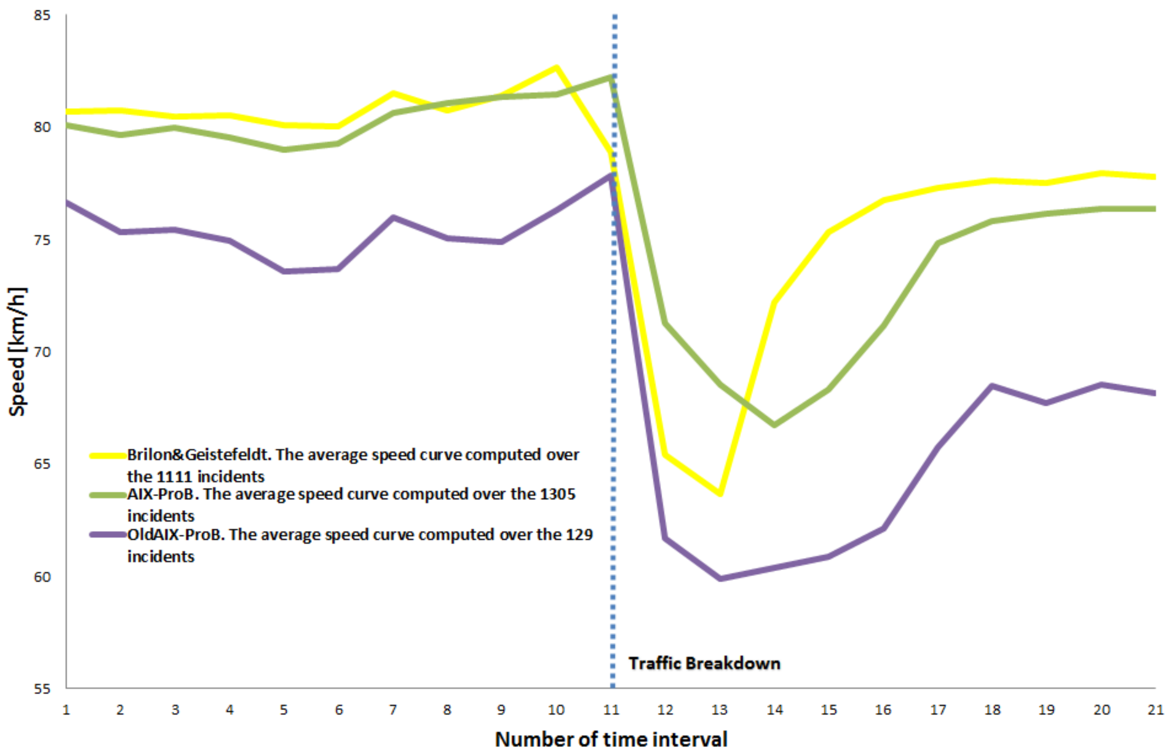

Figure 22: Average speed curves for different traffic breakdown recognition strategies

The traffic breakdown recognition ability results are showed at the Table 10. The method delivered the different results for different actual velocity values (v is equal to 60, 70 and 80 km/h) and thereafter it is distinguished between speed drops of 5 and 10 km/h. The traffic flow rate threshold stayed same. Note that for values representing the investigated time periods P1, P2 and P3 is valid statement that P3 ∈ P2 ∈ P1.

Table 10: Traffic Breakdown Recognition Ability

Traffic Breakdown Recognition Strategy	Number of recognized traffic breakdowns with respect to the pre-defined breakdown paramateres																		Total Number of Recognized Incidents by strategies
	Q_{15min} > 800																		
	v <= 60						v <= 70						v <=80						
	SD = 5			SD = 10			SD = 5			SD = 10			SD = 5			SD = 10			
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	
Brilon & Geistefeldt	12	12	0	6	6	0	300	300		74	74		1052	994	694	507	507	433	1111
Old Aix-Prob	10	10	0	5	5	0	46	46	11	22	22	11	129	127	92	103	103	92	129
AIX-Prob	19	17	4	12	12	3	179	172	73	91	88	60	861	814	402	464	457	304	1305

P1 ... (i-1,i+1) SD ... speed drop v(i) - v(i+1)

P2 ... i-1 v ... speed at at the interval i

P3 ... i Q_{15min} ... flow rate observed during 15 minute period

It can be observed that AIX-ProB has better recognition ability for the lower speeds and for higher speed drops. Considering actual velocity equal v = 60km/h and speed drops SD = 10, AIX-ProB reveals twice more breakdowns than Brilon&Geistefeldt and in the three cases it hits accurately breakdown at time interval i (as the only strategy). On the other hand, the AIX-ProB strategy has the highest total number of the recognized incidents (equal to 1305); if one links this value to the number of correctly recognized breakdowns, it appears that AIX-ProB produces many additional breakdowns. The Brilon&Geistefeldt has rather better ability to notice not so severe breakdowns, for example at the parameter values of v = 70km/h and SD =5, the Brilon&Geistefeldt analyzed correctly 300 breakdowns whereas AIX-ProB identified 179 and OldAIX-ProB only 46 breakdowns.

Since the data have strong stochastic character, the author decided to carry out the evaluation manually as well. The example of such an investigation is showed on the Figure 23. In the one-day observation period, the three traffic breakdown incidents were identified by the AIX-ProB recognition strategy. In the example, the all three recognized traffic breakdowns (see the red circles) can be considered as well-anticipated. Every traffic breakdown is followed by decrease in speed and at the same time, the flow rate values in the breakdown’s vicinity are raising. However, the Figure 23 implies the difficulties for a manual evaluation of accurate traffic breakdown recognition. If one wants to unambiguously decide whether all the breakdowns were correctly recognized, the evaluation requires detail investigation of all the relevant periods. It can be stated that the manual analysis is not sufficient due to a fact that enormous amount of data is normally used for the algorithm, however, it still stays valuable and necessary as an additional quality analyze.

The author randomly chosen the 15 traffic breakdowns determined by the AIX-ProB algorithm and analyze if the recognition decision was correct. For each incident (interval i), the ten previous and ten following time intervals for speed values and flow rate values were subsequent to evaluation. The author identified the 6 incidents as potentially wrong recognized and the 9 incidents as correctly recognized. An example of the 8 investigated incidents (randomly chosen) was plotted at Figure 24, complete data sample of 15 can be found at Appendix B.

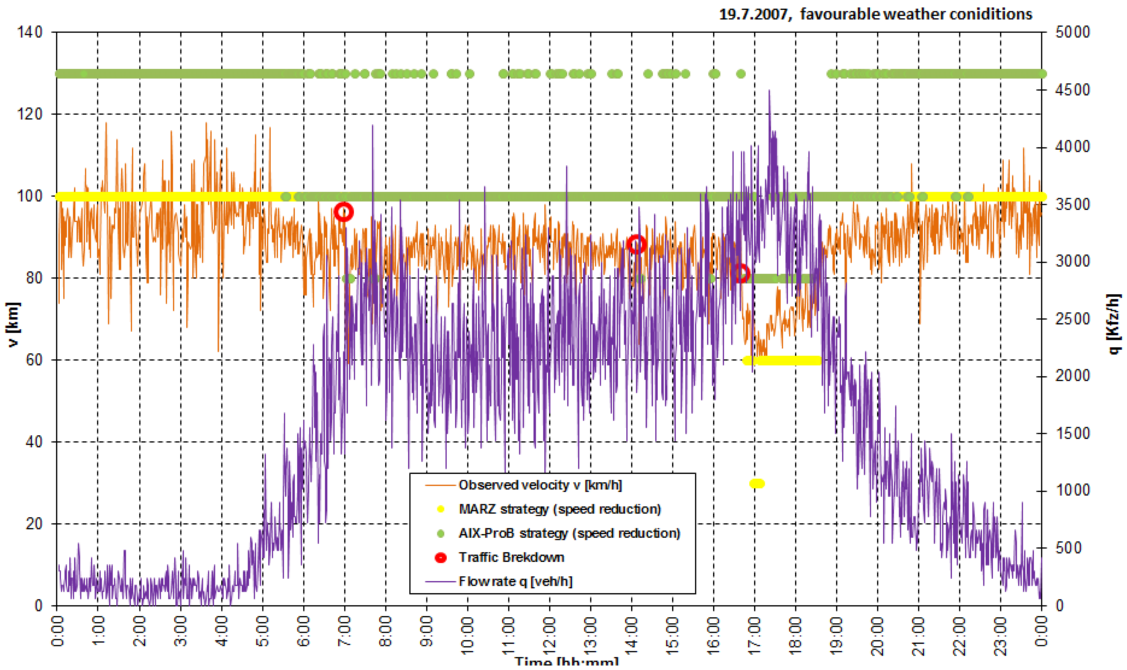

Figure 23: Manual Analysis Traffic Breakdown Recognition Ability

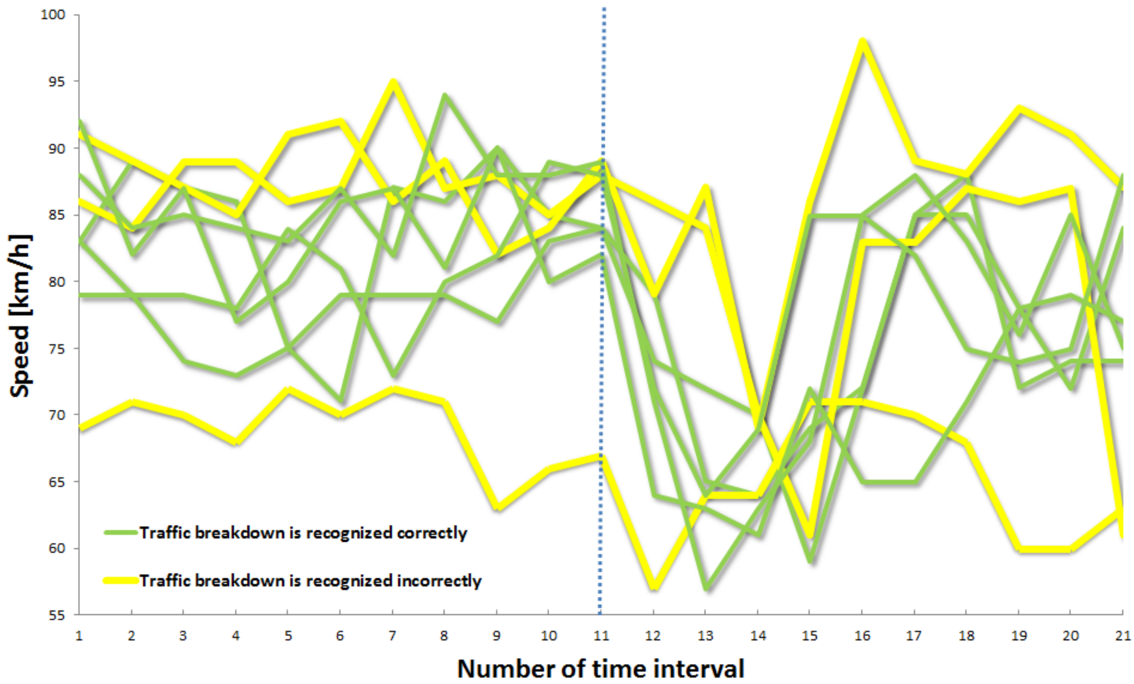

Figure 24: Detail of Manual Analysis of the Traffic Breakdowns Recognized by the AIX-ProB strategy

5.2 DATA LINEAGE

For the STSF, DR and FAR evaluation the twelve month (1.1.2011-31.12.2011) data acquired at the German highways, in section about 100 km was used. Note that the used values have two-dimensional extent where it is recognized between time and location of data collection. The following three main data sets were analyzed:

- Speed data

  Speed data measured with one minute time interval regarding to the specific time and freeway section.

- Jam data

  Jam data marks the intervals where the congestion was determined based on the AIX-ProB algorithm recognition strategy.

- Control values

  The speed reduction values delivered by AIX-ProB (100, 80, 60 and 30 km/h); additionally the speed reduction values for currently employed speed reduction algorithm - based on the "MARZ strategy", see MARZ99 (1999) – were used for possible need of referencing the AIX-ProB's result to an alternative strategy.

Additionally, the environmental data were employed; for example a level of wetness or a level of light.

The 59 918 400 data records were subordinate to the evaluation from which the 18 927 147 (31, 2%) were not available. The "clear" data obtained by filtering the unavailable days left 295 days for the further evaluation.

Further the traffic breakdowns according to the method presented at 5.1.2 were counted for 295-day sample. Considering the severe types of breakdowns, for v <= 60 and SD = 10 was counted 146 569 breakdowns, additionally for v <= 70 and SD = 10 was determined 248 184 breakdowns. For the less severe types of breakdowns, totally 191 156 (for v <= 60 and SD = 5) and 319661 (for v <= 70 and SD = 5) breakdowns were indicated.

Author used a capability of three-dimensional STSF analysis and compute so-called "congestion triggers". The congestion triggers are characterized as very first time interval, where the congestion was identified and from which a capacity incident continues in time/spatial extent. An example of the congestion triggers is showed in Figure 25. It was totally computed 7 592 triggers.

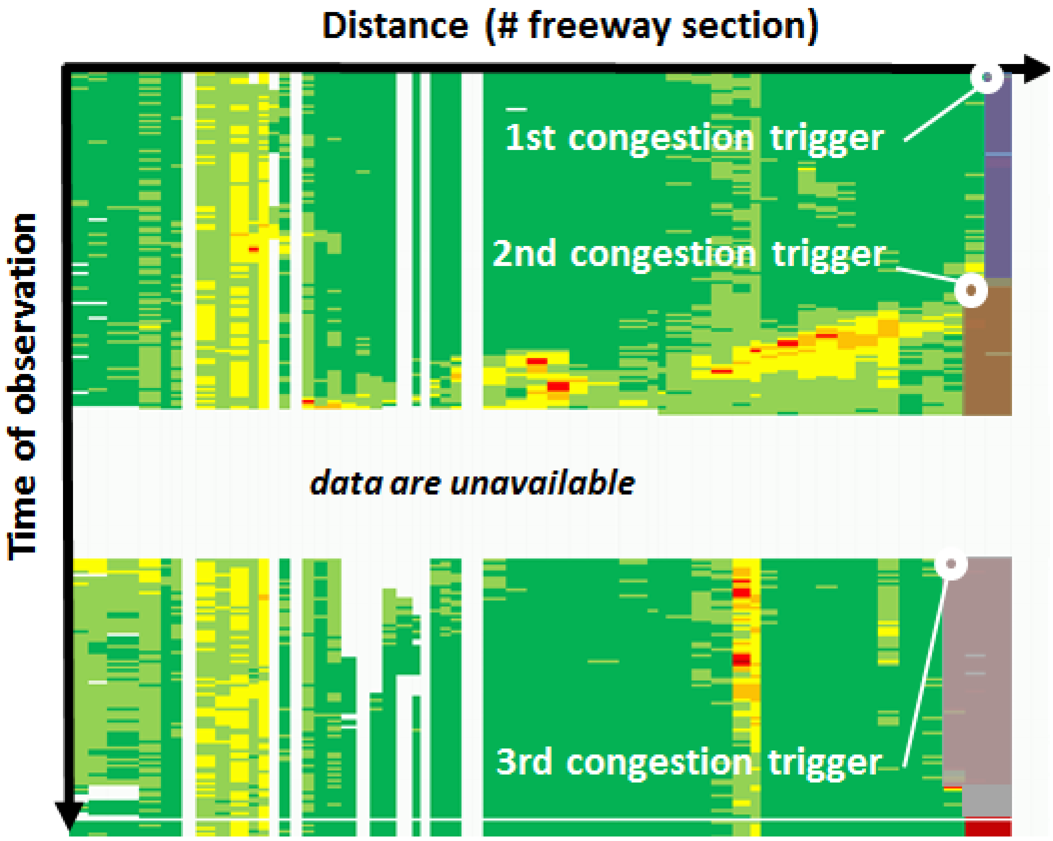

Figure 25: Examples of the congestion triggers

The amount of relevant breakdowns same as number of triggers create an image about a frequency and size of the traffic congestions at the given section. Moreover, these numbers can be used for "scaling" the algorithm's quality evaluation results.

5.3 STSF Evaluation

5.3.1 Visualization

Considering the fact, that the investigated data have three-dimensional character, the author decided to use MATLAB software to provide the three-dimensional visualization. This is appeared as a favourable alternative to the two-dimensional STSF plots, for example presented at Bertini et al. (2005) or Bogenberger (2004), which might have sometimes cases insufficient information value. Moreover the employed three-dimensional method allows a simultaneous visualizing of several layers in one chart; this is desired in case when it is necessary to plot the speed reduction values "over" the measured velocity.

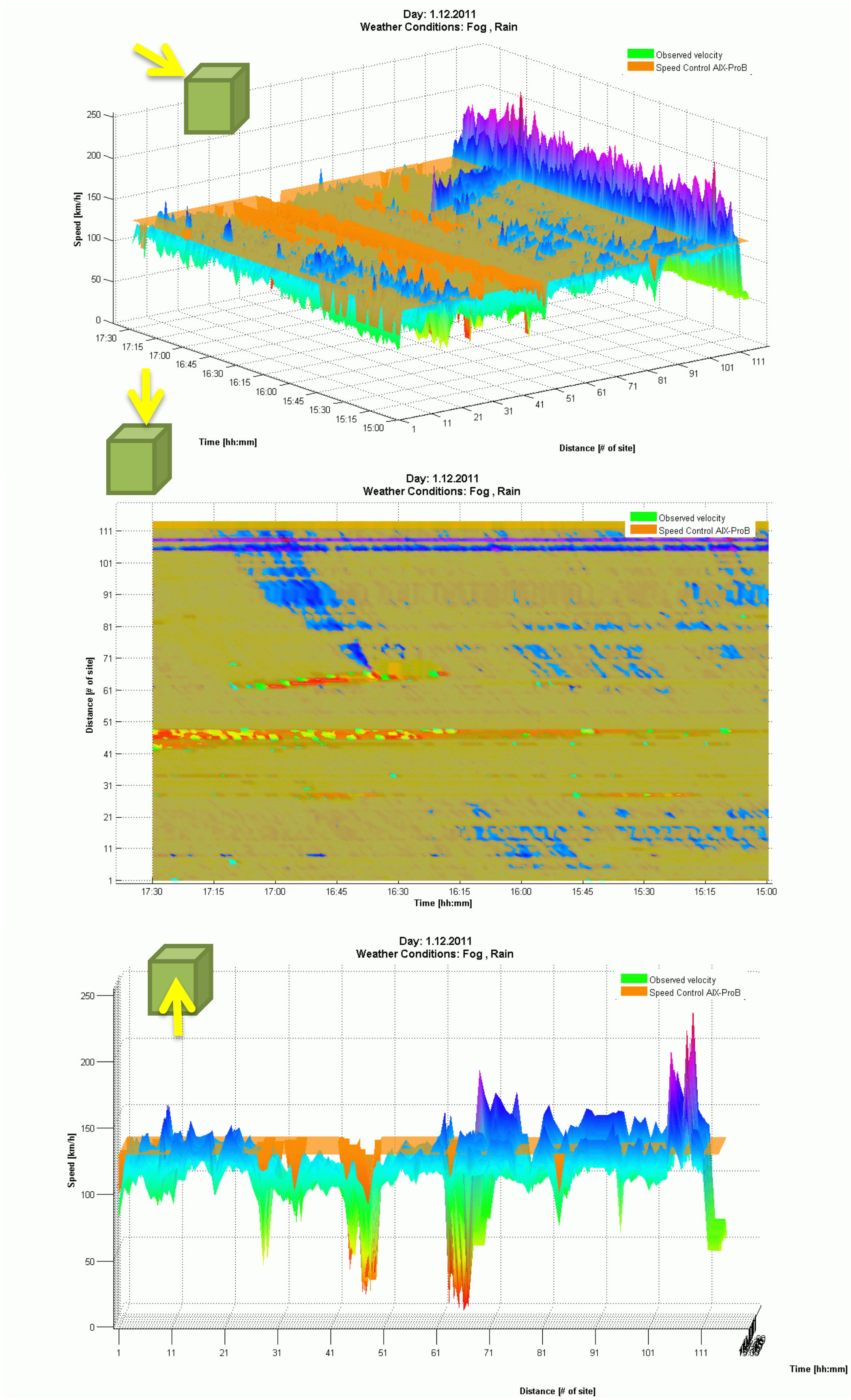

Figure 26: An Example of STSF Visualization

An example of the STSF visualization is presented in the Figure 26. The three different views reports the traffic conditions (velocity, see the continuous surface with color representing speed value) at given section, observed on December 1st between 15:00 and 17:30. At the same time, the control pattern for the AIX-ProB (see the orange continuous surface) is plotted as well. Note that the speed value equal to 130 of control pattern represents a situation when the control is inactive (no speed reduction is showed).

The STSF visualization documenting some investigated traffic situations (will be further discussed at the chapter 5.5) can be found at Appendix C.

5.3.2 STSF Criteria Evaluation

The following sub-chapter presents the STSF analysis results considering a set of the four fundamental criteria defined at chapter 4.4.2.

The probably most critical criterion of the STSF evaluation is the missing control. The AIX-ProB does not cover the congestion area of 14 861 intervals with average size of missing of 50.72 intervals which were not covered per day. Taking into account that totally 308 214 intervals were defined as congested by the AIX-Prob algorithm; the missing control takes 4.82% of the whole congestion area size.

The speed reduction time relevance criterion evaluated the algorithm's quality regarding to the speed reduction preceding (ΔT_1) and following (ΔT_2) the congestion incident, the results are showed in Figure 27. Whereas AIX-ProB reduces speed excellently only in 13% (1424) of all congestion preceding reductions, the speed reduction stays after the congestion excellently in 64% (7104) of all cases. The significant difference between reduction during ΔT_1 and ΔT_2 can be caused by time relevance criterion parameters settings. The poor quality ranking for ΔT_1 is observed in case that a reduction is too late (<1:00) or too early (>5:01), see chapter 4.4.2.1. The author supposes that especially too early threshold for poor ranking can distort the results since in some cases it might be intended to start with speed reduction more than five minute before a jam incident has occurred (e.g. in case of very severe congestions).

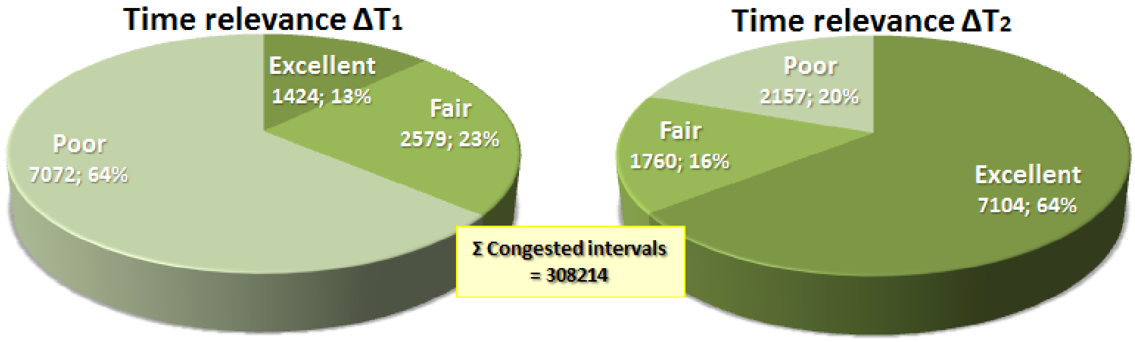

Figure 27: Speed Reduction Time Relevance Criterion for AIX-ProB algorithm

The previous criterion evaluated early or late speed reductions with respect to their time extent. Additionally, the early or late speed reductions based on a spatial extent were investigated. It was found that the speed reductions before the congestion was incorrect in the 104 014 cases for ΔD_1 and in the 39 723 cases for ΔD_2. Similar to the time spatial relevance criterion problem described above, it can be desired (for example) to have larger distance margin than only one previous gantry for speed reduction of 60 km/h. Considering the total amount of the congested intervals, the both results ($\Delta D_1/\Delta D_2$) for spatial criterion are appearing relatively high. This criterion meets problem that distance is measured in the section sites units. So it is not currently distinguished whether two directly following sites are at distance of 500 meters or 2 kilometers, their distance is equal to 1.

The last STSF criterion evaluates the control mismatches. The results outlined at Figure 28 unambiguously prove that for the higher mismatch occurrence (around six times more than the total number of traffic jam incidents) are responsible mismatches of 100 km/h speed reduction with the total amount of 182 432 mismatches (98%). These types of mismatches, however, do not rapidly influencing the algorithm's quality since the reduction on the 100 km/h is not rather weighty. Since AIX-ProB is characterized by great preventive nature, the higher numbers for this type of mismatches were expected. Moreover, as was described in the chapter 4.4.2.3, some of the revealed mismatches can be actually regarded as proper control interventions which were created in order to maximally reduce potential capacity incident. The critical are mismatches of 60 km/h and 30 km/h since high occurrence of these events appreciably influence the system trustworthiness by drivers. Note that total amount of control intervals (within valid sample of data) is equal to 2 342 880; in contrast to this enormous number, the AIX-ProB mismatches the speed reduction of 60 km/h in 1 123 cases and the speed reduction of 30 km/h in 1 829 cases.

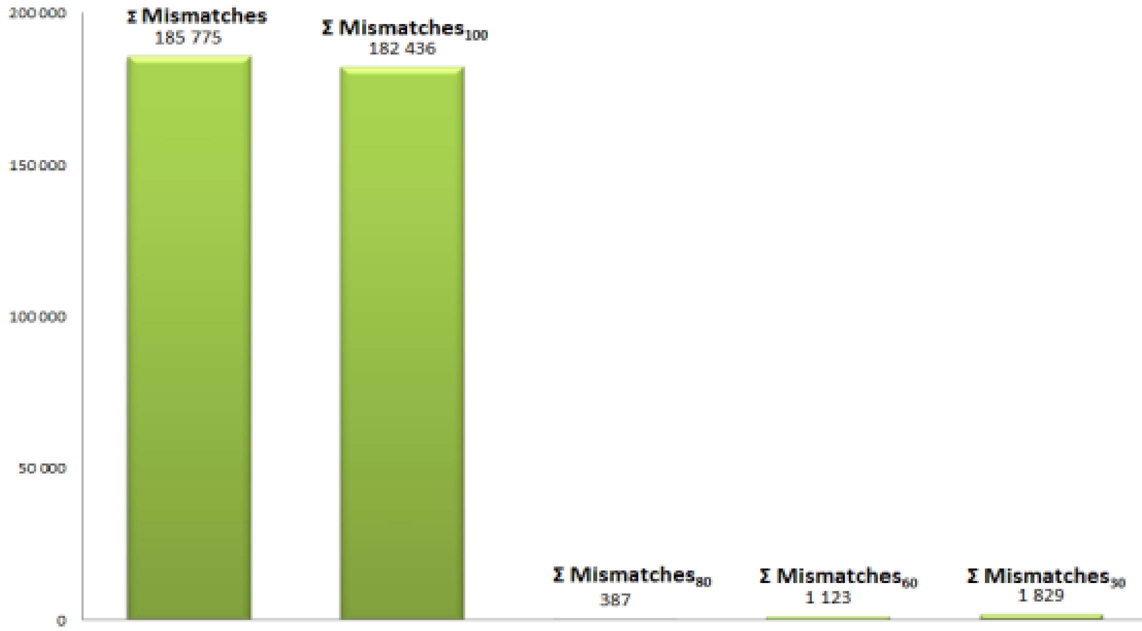

Figure 28: Control Mismatches Criterion Regarding the Specific Speed Reduction Value

5.4 DETECTION AND FALSE-ALARM RATE EVALUATION

In contrast to the STSF criteria where the specific criterion determining the particular algorithm quality aspects, the detection and false-alarm rate lay down the overall quality measures. Additionally, the both of measures are computed in relative numbers that provides easy-understandable results.

Reminding the assessment techniques and findings introduced by Bogenberger (2004), which were summarized at 2.2.4, specifically the use of the detection and false-alarm rate chart with the four extreme cases. The author randomly chose sample of three days and undertake the evaluation where the values of the both measures are differed by the speed reduction value. The results are outlined in Figure 29. It can be clearly seen that AIX-ProB performed the speed reductions in the all three cases solidly. Receiving the higher values of detection rate and corresponding lower values of false-alarm rates, the points tend to the positive extreme (Case 1). In the other words, the AIX-ProB tends rather to a state where the most of congestion cases is covered by speed reduction, and at the same time, the minimum of the “redundant” (false) controls are applied. If one follows the curves’ course, it testifies the assumption that the higher speed reduction values experience the higher values of detection and false-alarm rate. This is caused due to a fact that during the higher observed speed values is higher values variety reached.

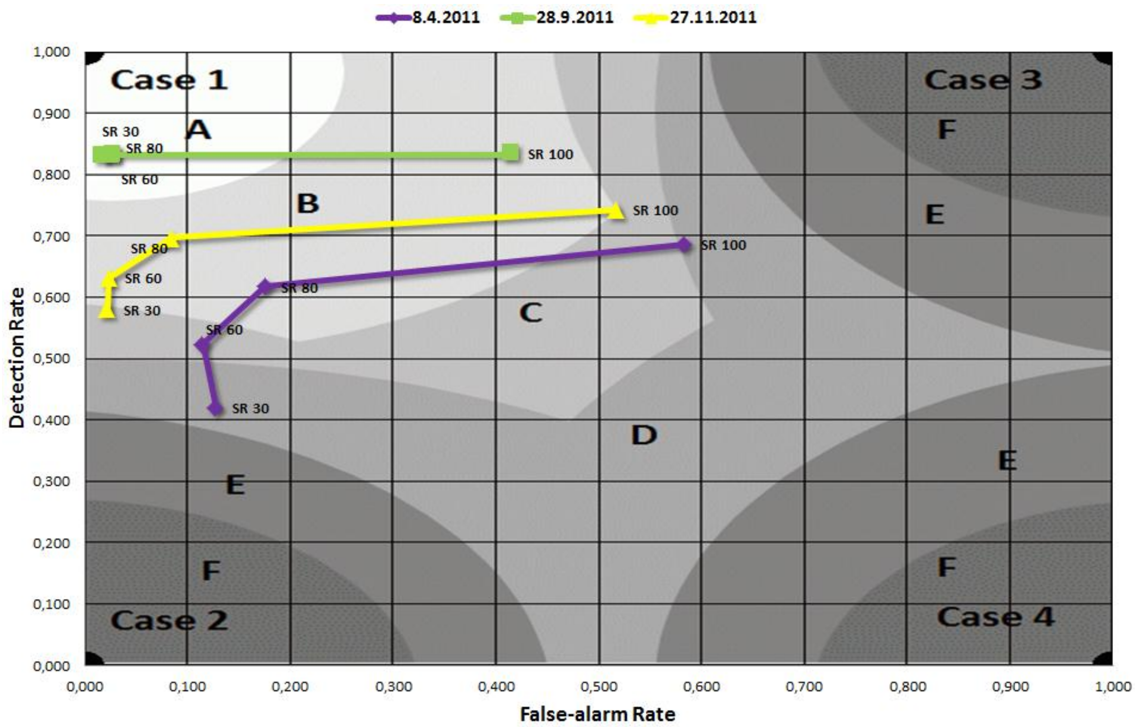

Figure 29: Detection and False-Alarm for the Three Randomly Chosen Days for AIX-ProB

The previous findings are additionally proved by the average rates. The year-round averages (considering available data) are showed in the Table 11. However, it appears that for evaluation is the simple mathematical average insufficient. The reason is that such an approach does not distinguish an "importance" of the speed reduction. For example, consider a situation where FAR_{80} is equal to 70% in the first case and in the second case a capacity incident delivers FAR_{80} equals to 30%. By computing an average, the FAR_{80} equals to 50% and it results in the conclusion that the algorithm produces 50% of unwanted speed reductions.

Table 11: The Year-round Average Detection and False-alarm Rate

FAR_{100}	FAR_{80}	FAR_{60}	FAR_{30}
0,61	0,34	0,28	0,26
DR_{100}	DR_{80}	DR_{60}	DR_{30}
0,57	0,51	0,44	0,38

Naturally this does not describe the real algorithm performance. For example, if in the first hypothetical example was the total congestion size ten times smaller than in the second case, one would rather expect FAR_{80} tends to 30%. To solve this problem, the author introduced weighted rates. The weight values have been assigned based on the empirical investigation of congestion size that is exposed to control. The weight value of 0.6 was assigned to the major congestion incidents with area size higher than 5000, weight equals to 0.3 reflects the medium incidents in size less or equal to 5000 and more than 2500 and finally weight of 0.1 was applied in case of the congestions less or equal to the incident in size of 2500. Remind that DR and FAR follows the three dimensional extent; then for example congestion in size of 2500 can be ten 5-kilometer incidents lasts for 50 minute occurred within the observation period, in this case lasts for one day. The results are showed in the Table 12. In contrast to the numbers presented in the Table 11, here it reflects the severity of an incident and the values are rather drawing a conclusion about the algorithm's quality. As was expected, the rates describing the speed reduction delivered the highest value of FAR, however, corresponding DR is smaller than other values of detection rate. This result would not be concluded negatively; it can be interpreted as an algorithm's capability to recognize and rather "control" more severe incidents (occurring at lower speeds where the need of an action is more urgent). The results are strongly influenced by the weights defined by the author.

Table 12: The Year-round Average Detection and False-Alarm Rates Considering the Traffic Congestion Severity

$FAR_{100WEIGHT}$	$FAR_{80WEIGHT}$	$FAR_{60WEIGHT}$	$FAR_{30WEIGHT}$
0,43	0,25	0,21	0,20
$DR_{100WEIGHT}$	$DR_{80WEIGHT}$	DR_{60}	$DR_{30WEIGHT}$
0,48	0,62	0,57	0,52

5.5 Comparison to the Currently Used Control Strategy

The initial idea is not to provide the comparison. This would require specific methodology that reflects some comparison measures. The master thesis shows instead a complex technique that has potential to help not only to evaluate the algorithm overall performance but also describes the indicated quality measures in order to receive an image about algorithm's behavior and consequently subordinate such an image to the evaluation, which would for example evaluate the algorithm's preventive nature.

However, outline the comparison would help to indicate potential benefit of algorithm deployment. The referenced control strategy that currently applied as VSL algorithm at

German and Austrian freeways (commonly called MARZ) is based on the principles stated in MARZ99 (1999). The available data is controlled by MARZ and therefore it can be used for algorithm evaluation. Using the same sample of data for AIX-ProB evaluation, it meets a limitation because the drivers do not respond on AIX-ProB (its speed reductions are applied in test environment) but on the speed limits proposed by MARZ (these limitations will be further discussed at chapter 6).

As was explained at chapter 2.1.3, roadway capacity varies over the environmental conditions. AIX-ProB has a capability of perceive and utilize information about the actual weather condition as was described at chapter 3.2. At this point, the author gives a hypothesis that the AIX-ProB algorithm shows more quality control performance than the traditional algorithms (in this case MARZ) which do not reflect the actual environmental conditions. In order to investigate this statement, the five randomly chosen days with unfavorable weather conditions were used for a comparison. The results are showed in the Table 13. Note that the first two rows present the annual average results (over the available data).

Table 13: Comparison of AIX-ProB and MARZ

	Characteristics	Date	Measured interval	Missing	Mismatches	Mismatches60	Mismatches30	Time Relevance - Excellent	Time Relevance - Fair	Time Relevance - Poor	Spatial Relevance - ΔD1	Spatial Relevance - ΔD2
AIX-ProB	Annual	1.1.-31.12.		14 861	185 775	1 123	1 829	8 528	4 339	9 229	104 014	39 274
MARZ	Annual	1.1.-31.12.		70 483	374 270	1 811	285 707	6 353	2 669	5 382	113 720	52 706
AIX-ProB	Rain, Snow	3.2.	14:30 - 17:30	20	187	0	1	16	5	19	88	19
MARZ	Rain, Snow	3.2.	14:30 - 17:30	118	766	16	502	6	6	8	121	16
AIX-ProB	Rain	16.5.	7:30 - 9:30	22	303	0	1	13	14	21	129	34
MARZ	Rain	16.5.	7:30 - 9:30	168	726	16	455	6	6	8	121	16
AIX-ProB	Rain	11.6.	6:30 - 9:30	19	192	0	1	13	5	10	74	16
MARZ	Rain	11.6.	6:30 - 9:30	49	611	16	349	5	5	6	107	8
AIX-ProB	Rain	8.9.	14:30 - 17:30	23	387	0	0	19	9	12	82	32
MARZ	Rain	8.9.	14:30 - 17:30	92	493	16	185	6	5	7	110	11
AIX-ProB	Rain	6.10.	14:30 - 18:00	46	630	1	3	46	16	48	263	195
MARZ	Rain	6.10.	14:30 - 18:00	283	670	16	389	12	12	22	220	106

The table clearly indicates the new algorithm’s benefit. During the five randomly days was found that MARZ has averagely 5.5 times higher missing rate than AIX-ProB. An interesting is a comparison of the critical mismatches (for speed reduction of 30); here AIX-ProB reaches the numbers around zero and the concurrent algorithm delivered the results of hundreds. It can observe that the MARZ algorithm reaches lower numbers for the speed reduction time-relevance criterion. However, this cannot be considered as an advantage of the control strategy. In this case, the smaller numbers rather implies that the congestions were not covered at all (thus the time-relevance can be investigated). This can be confirmed by a fact that MARZ showed the smaller numbers at all time-relevance rankings and at the same time showed much higher control missing rate than AIX-ProB.

In the next step, the DR and FAR chart (see was created for data sample acquired on February 3rd, May 15th and October 6th (as were presented in the Table 13). This graphical interpretation comes to the conclusions outlined in the previous paragraph.

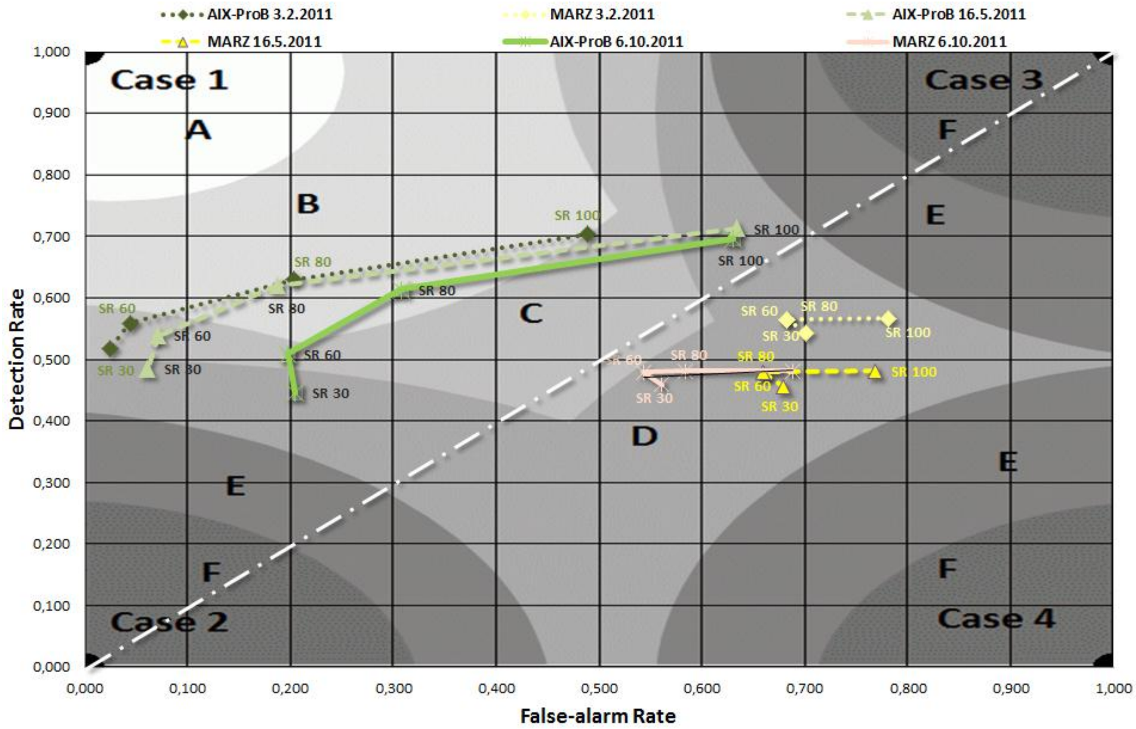

Figure 30: Detection and False-Alarm Rate for AIX-ProB and MARZ

Comparing the both rates separately, AIX-Prob and MARZ have similar level of detection rate for speed reductions of 30 and 60 km/h. In case of the reduction of 80km/h, AIX-ProB becomes slightly better in the matter of congestion detection and this trend is clearly proved for the speed reduction of 100 km/h. The false-alarm clearly indicated the AIX-ProB quality and it can be concluded that AIX-ProB experiences its highest FAR (considering the speed reduction of 100km/h) at the area (see FAR between 0.55 – 0.65) where MARZ meets its lowest values of FAR (however in this case it is speed reduction of 30 and 60 km/h by MARZ).

The following STSF charts (see the Figure 31 and the Figure 32) are documenting some conclusion presented by the STSF four-criterion analysis and by the DR & FAR analysis. It shows an example of a situation on May 16th (7:30 – 9:30) for both of the speed reduction strategies.

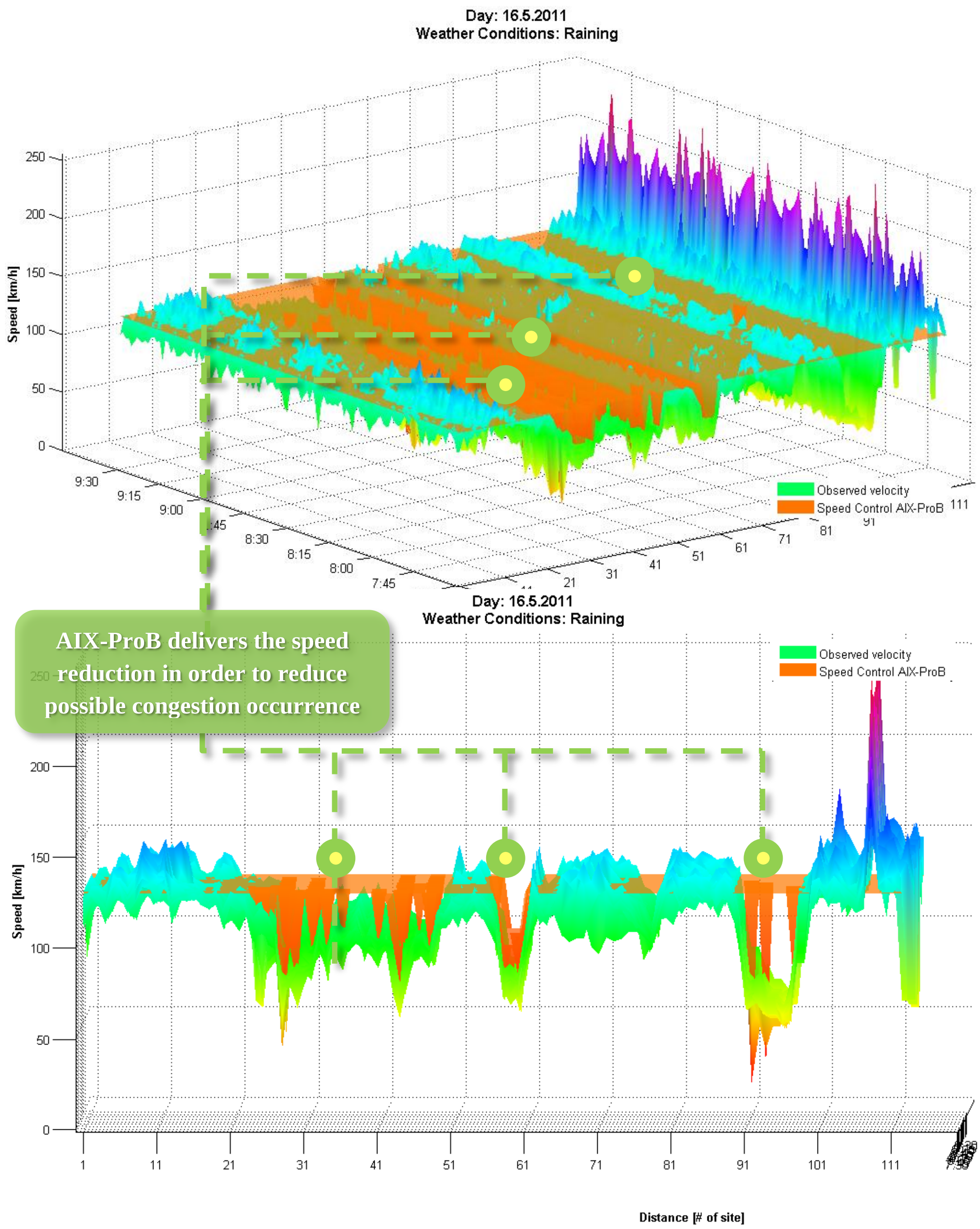

Figure 31: STSF Visualization for AIX-ProB, data measured on May 16th, between 7:30 – 9:30

The upper example (see the Figure 31) presents “proper control” by AIX-ProB where the algorithm proactively reduces speed (corresponding to the present and directly preceding incidents). However, some small missing control events can be found around the site 90 (7:30 – 8:15).

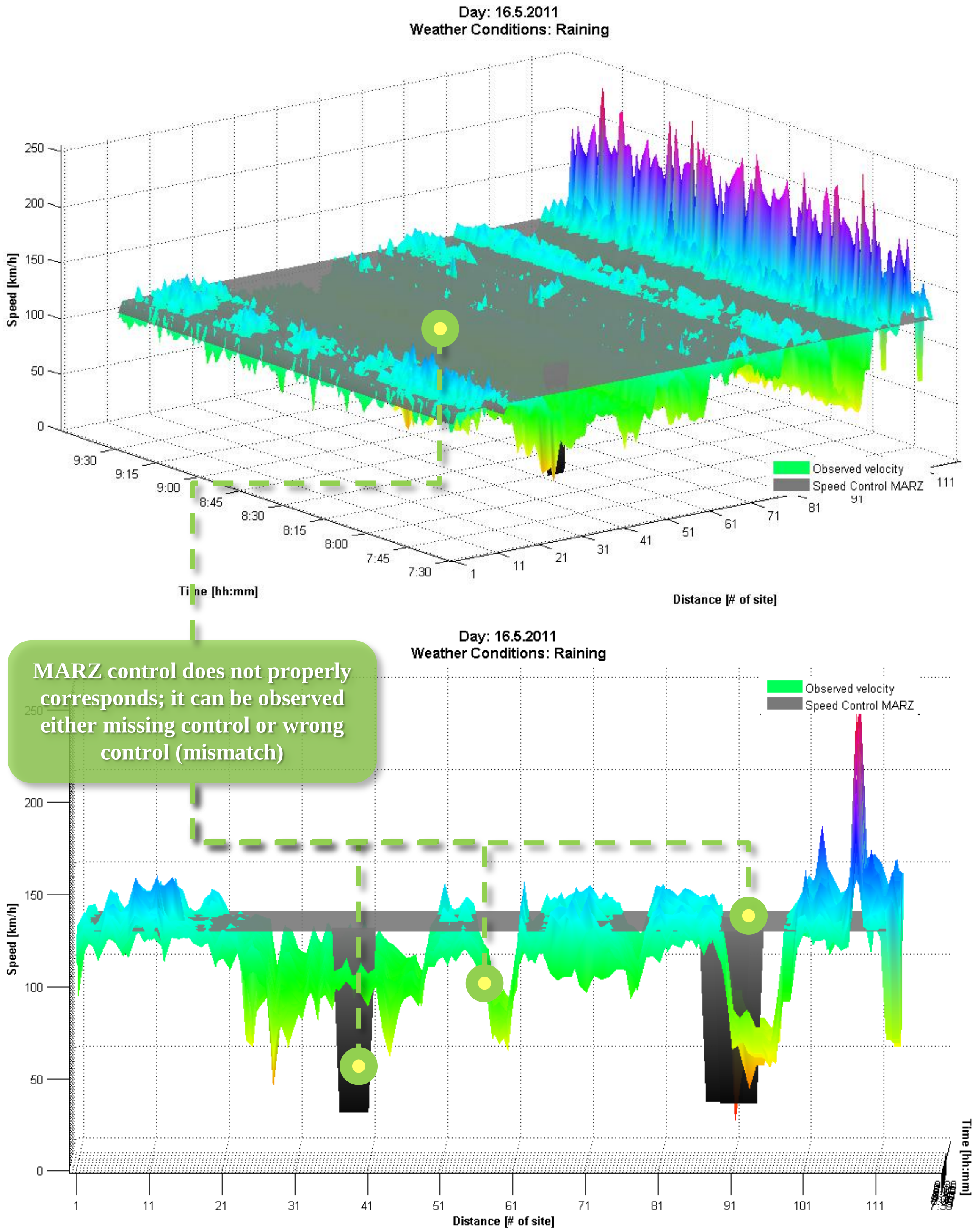

Figure 32: STSF Visualization for MARZ, data measured on May 16th, between 7:30 – 9:30

The MARZ's example (see Figure 32) indicates missing control between the sections 21 – 61 (over the whole observation time period) with the clear examples of mismatches (between sites 35 – 40, around 8:15), the control missing (see sections 55 – 60) and the some error combination can be observed around the site 90. The STSF visualization for the rest of investigated days is enclosed at Appendix C.

At the end, the hypothesis stated at this sub-chapter can be confirmed. AIX-ProB proved much better performance in the all evaluated criteria. This was actually expected due to a fact that the AIX-ProB can better anticipate a real traffic situation with utilizing the actual environmental condition information (a principle of the utilization was described at the chapter 3.1).

5.6 EVALUATION SUMMARY

In the first step, the traffic breakdown recognition ability was evaluated as a necessary condition of successful stochastic capacity algorithm employment. Using a method design of the highest speed drop identification for recognition quality evaluation, AIX-ProB pointed rather higher number of the traffic breakdown. This could be due to algorithm's preventive nature. Comparing to the recognition strategy that was adapted from the Brilon&Geistefeldt strategy, AIX-ProB tends to accurate traffic breakdown recognition (or slightly earlier); Brilon&Geistefeldt showed to be late by one time interval. Additionally, it was found that AIX-ProB has good ability of revealing the most severe traffic breakdowns, for example during the one-year period AIX-ProB indicated 191 156 breakdowns for $v <= 60$ km/h, SD = 10 km/h and 248 184 breakdowns for $v <= 70$ km/h, SD = 10 km/h. In contrast, the Brilon & Geistefeldt strategy aims on the less severe breakdowns typically with $v<=80$ and SD = 5 km/h.

Some important findings were revealed by the STSF four-criterion evaluation. AIX-ProB does not cover the congestion only in 4.8 % cases comparing the complete traffic congestion size measured within one year. The algorithm experienced higher poor ranking in term of time-relevance speed reduction criterion. However, how was described before this would be still understood as algorithm's ability to at somehow preventively react. Remind that criterion is greatly influenced by a parameters setting which should (in future) correspond to the policy maker demands. It appears that initial design for time-relevance speed reduction needs to meet a change of the parameters determining the quality. Specifically, poor ranking should be linked by the quality level for $\Delta T1 < 1$minute (this is real poor control quality) and the quality level for ΔT1 > 5 minute (in this case, it requires further investigation). Similarly, the parameter settings can be a cause of the relatively higher numbers obtained at spatial-relevance criterion. Additionally as was stated before (see chapter 5.3.2), the current evaluation does not distinguish a distance between the freeway sections. AIX-ProB demonstrates good quality regarding the mismatches when 98 % represent the situations where the algorithm posts speed reduction of 100 km/h (so only 2 % can be considered as serious mismatches). This confirmed an assumption of higher mismatches at the higher speed values when the higher speed variety obviously delivers a higher number of (false) breakdowns. The algorithm's objective is to proactively perform preventive speed reduction. Having perfect information about upcoming future, the number of mismatches (even with respect to the algorithm's high preventive character) would be significantly lower (tends to zero); however this is of course not possible.

Overall good AIX-ProB is performance was also proved by DR and FAR analysis. Using a graphical interpretation (see Figure 29) outlines that AIX-ProB meets higher DR and keeping the FAR under the level of 50 % (considering the speed reductions of 30, 60 and 80 km/h). The only higher FAR was experienced for the speed reductions of 100 km/h; this expected phenomenon was described in the previous paragraph. In the other words, the DR&FAR curves (Figure 29) are rather placed in the vicinity of upper left corner that represents the positive.

In the last of the evaluation, the author made a step toward to a comparison approach. With the currently deployed control algorithm MARZ as reference, the AIX-ProB strategy proved better performance in the all evaluated criteria. MARZ showed 5.5 higher control missing rate as the most important evaluated criterion. Additionally AIX-ProB provides incomparably lower mismatch rate for speed reduction of 30 and 60 km/h. AIX-ProB delivers greatly higher mismatch rate speed reduction of 100 km/h, however, these mismatches are not critical and they are not seriously influence the quality. The results presented in comparison (see chapter 5.5) were based on the example of five observation periods acquired during the bad weather conditions (rain, wet surface). Thus, it confirms the empirical researches which refuse the traditional deterministic roadway capacity approach for its insufficient accuracy of current situation description. Eventually the overall one-year period results delivered the similar results (see the first two rows in the Table 13). Among the others, it shows 4.7 times higher missing rate.

6 CONCLUSION

The conclusion body results in four subchapters, the subchapter 6.1 presents the thesis results according to the objectives defined in the thesis beginning (see the chapter 1 and specifically the subchapter 1.2). The subchapter 6.2 puts down the main findings regarding the AIX-ProB evaluation and its implications in wider context. The subchapter 6.3 highlights some interesting researching topics revealed during this master thesis. The last subchapter states the main thesis message.

6.1 EVALUATION CONCLUSION

The evaluation conclusion can be split into the two blocks which meet the two main objectives – evaluate the algorithm and analyze if the developed "platform" (this term covers the designed methodology, used parameters and SW application) is suitable for further use.

Regarding to the first block, the algorithm prove good performance in the all of the analyzed criteria. Especially algorithm's ability to reveal all the congestion incidents is enormous (congestion is not revealed only in less than 5 % of all traffic capacity incidents). Furthermore, the master thesis confirmed previous researches that emphasize limitations of the capacity deterministic approach as a main stream in the current VSL practice. The thesis empirically proved that by using stochastic approach the desired traffic management strategy objectives (e.g. reach a low FAR with solid level of DR) can be reached much better. The complete summary about results, algorithm's quality and comparison to the widely deployed MARZ control strategy is provided at chapter 5.6.

The several issues have occurred in the second block. First of all, there were not available reference requirements on the evaluation tools. Due to a lack of the guideline, the author created a system of user needs which were further discussed and designed with ASFINAG as further user of AIX-ProB. This procedure was later proved very useful. It helped to define a synthesis of the evaluation goals where fundamental algorithm's quality (primarily the control missing criterion) and algorithm's preventive nature (e.g. time-relevance criterion or DR analysis) were reflected as two main aspects. Whereas the detection and false-alarm analysis offers a scale from 0 to 100 % completed by the specialized chart (see for example Figure 29 or Figure 30), the interpretation of 4-criterion STSF analysis can be problematical. As a solution for successful method application, the author propose to compare the received results to the total the congestion size or alternatively to the number of breakdowns. In general, the STSF analysis showed potential for next use since it provides complex tool that is able to deliver more comprehensive results. For example, it allows introducing some additional features, advanced graphical interpretation (e.g. “layering” when clear image of the speed reduction layer envelops the speed values surface) or to analyze characteristics which could be revealed only difficultly with two-dimensional evaluation (with respect only to time extent or spatial extent), a typical example is the control mismatch criterion. However, as was stated before, the results enhanced by the two-dimensional input values shows higher complexity and it require higher effort in their interpretation.

The traffic breakdowns and their recognition raised another problem. Considering the high randomness as a typical feature of traffic data, the most accurate way of an investigation, whether an incident is breakdown or not, is to obtain the manual analysis (and results then compare with the traffic breakdowns indicated by the algorithm). This method is the most accurate but not sufficient due to enormous amount of data. The all used traffic breakdown recognition “automated methods” has suffered from the strong influence of pre-defined method’s parameters (e.g. value of speed drops, number of considered intervals). The author proposes here for future, a deeper discussion with potential user (agency) and subsequently defined the parameters based on the strategy maker’s demand.

One of the thesis results limitations, regarding the proposed methodology, is the fact that whereas the input data (speed reductions) for MARZ algorithm respects real observed values, the data provided by AIX-ProB were gained from the test environment and basically reacts on the already “controlled” traffic stream (controlled by MARZ). Among the others, this does not allowed to carry out a final independent comparison with other relevant strategies. Note that this situation reflects common practice when a freeway operator cannot employ the newly proposed algorithm for its testing in real environment. If the operator once decides to re-build the system and add the new control algorithm, it has to absolutely sure that the change brings the desired results (better comparing to a current state) with no additional risk. But actually more important fact is that lacking data does not allowed research some of the defined user needs regarding the algorithm behavior. For example, the fundamental measure like travel time cannot be really evaluated because the collected traffic data meet control interventions from the concurrent algorithm.

6.2 EVALUATION FINDINGS

AIX-ProB has delivered several positive findings that pre-determine the algorithm for its further possible deployment. The author supposes that having accurate VSL, corresponding the real traffic and reflecting the environmental conditions, can help fulfill traffic policy tasks. In future, the tool like AIX-ProB would radically help in the recently occurring transportation challenges; mainly reduce a potential threat of the gridlocks or enormous traffic congestion incidents caused by the progressively raising traffic demand (responding among the others to the growing population or higher people desire for mobility). Here, the intelligent traffic tools like AIX-ProB meet not only the road operators particular requirements and objectives (as a subject responsible for their operating), but also criteria like society security or freedom of mobility. Another hypothesis would state that having the well-funded traffic management infrastructure considering VSL as its essential part, the great economic losses can be reduced regarding the fact that throughput is going to be stabilized (or increased) and the freight road transport can then operate in smooth traffic conditions. As was stated before, the algorithm experienced great results in the evaluated measures. The success is (among the other mentioned aspects) caused by reflecting the environmental data. The author states the hypothesis that further research over the input environmental data that should carry the complex system of relevant environmental conditions can improve algorithm behavior. The chapters 3.1 and 3.2 describes some fundamental AIX-ProB's capabilities; besides the already discussed fact of reacting on the real current conditions and proactive preventive approach, the author see great benefit in easy algorithm parameterizing and thus much favourable implication. It removes a burden of parameterizing each gantry separately on the freeway in order to reach the desired performance. A freeway operator agency just defined the acceptable level of breakdown probability.

The fundamental problem that have not been solved (and author considers this issue beyond the scope of this thesis) is to unambiguously determined what is the traffic congestion. For example, is the continuously moving queue of the vehicle on freeway by speed of 70 km/h congestion? The similar questions remain unanswered.

6.3 Further Research

The first suggestion is to go beyond the thesis scope and try to evaluate a benefit of the new stochastic approach regarding the safety impact. As was stated before, the methodology was created according to the set of user needs. However, the current state of evaluation does not cover the questions of safety improve, economic or travel time benefit. These indicators are important for the traffic management tools (like AIX-ProB) deployment. Based on such research, the algorithm would better respond to the needs when the policy desires to prioritize safety issue over the other criteria; the VSL algorithm would then contained probably much more strict decision policy. Additionally, the crucial is a balance between planning the system as safety mean and planning the system aiming on the higher level mobility. Similar questions were already pointed out in Mirshahi et al. (2007).

The author proposes further research on critical VSL applications like speed reductions at the vicinity of construction sites or traffic accidents. These incidents are currently run by the pre-defined scenarios where usually a high amount of manual decision effort is needed. Thus it is intended to research whether these events can be generally classified by a condition set and subsequently, what is the algorithm behavior and control quality for these extreme cases.

During the master thesis research was indicated the critical issue of current traffic management state. The traffic engineering science recently developed great effort in order to maximally improve enforcement on freeways. However, it appears that perfectly operating enforcement is in direct contradiction to the active traffic management (concretely VSL). Consider a specific case, when the speed profile at given section during the observed period decreased below some critical threshold. By using VSL control strategy, it desired to preventively display speed reduction in order to smoothing and harmonizing traffic stream. Assume that traffic stream has reached saturation after some time and further tends to reconstructing into to the initial conditions. System now expects some kind of violating (speeding) from drivers; this violating triggers a VSL and implies that a capacity incident has been overcome and there is no more need to show speed reductions. This fundamental VSL principle can be found in MARZ99 (1999). The vehicles are however further restricted by the enforcement which causing the drivers' refusal for speeding. Consequently, the trigger (implying the end of congestion and canceling the speed reduction) is not delivered and VSL holds the restrictions. Making full circle, the enforcement functionality goes against the VSL. The author suggests to research further a balance between both mentioned systems which preserve their operability.

6.4 CENTRAL MESSAGE

The master thesis has concluded the following findings:

- The stochastic approach can determine the roadway capacity more accurately than the traditional deterministic method.
- The newly proposed algorithm AIX-ProB has great preventive capability.
- The created evaluation methodology delivered the solution for objective measuring the VSL control algorithms quality; however it has further potential to be applied even on the another types of the traffic management strategies, for example on lane management system or traffic information message system.
- The developed SW tool can be applicable on the enormous amount of data same as on different traffic control algorithms.
- Taking into account the control algorithm objectives, the traffic breakdown employment delivered the desired results; nonetheless it is suggested to undertake the more comprehensive research about its unequivocal characterization.

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APPENDIX

APPENDIX A: EVALUATION CODE

The Appendix A presents the evaluation macro coded in Microsoft Visual Basic for Applications (MS Excel VBA). Note that code was designed into the separate sub routines where each routine covers a specific evaluation method (STSF missing criterion, mismatch criterion, time-relevance criterion, spatial-relevance criterion and detection and false-alarm rate). The first routine initializes the input data and calls the related sub routines.

```
Sub initialization()
Dim InputLine, InputArray
Dim FolderName As String
FolderName = "C:\AIX-ProB\source data"
Open FolderName & "\Velocity.csv" For Input As #1
Open FolderName & "\Jam.csv" For Input As #2
Open FolderName & "\Control.csv" For Input As #3
Line Input #1, InputLine 'reads the 1st line
Line Input #2, InputLine 'reads the 1st line
Line Input #3, InputLine 'reads the 1st line
'# of evaluated days (each day is re-writen by the new one)
For d = 1 To 365
    DoEvents
    '# time intervals, one day = 1440, 114 detectors
     For i = 1 To 1440
        DoEvents
        For f = 1 To 3
            DoEvents
            Line Input #f, InputLine
            InputArray = Split(InputLine, ";")
            For j = 1 To UBound(InputArray)
                DoEvents
                Worksheets(f).Cells(i + 1, j) = InputArray(j)
            Next j
        Next f
    Next i
    Call missing
    Call mismatch
    Call spatial
    Call time
    Call rates
Next d
Close #1
Close #2
Close #3
End Sub

'missing control criterion + computing data completeness
Sub missing()
Dim i As Long
Dim j As Long
```

```
Dim inputEntry As Long
Dim firstBlankCell As Range
Dim stackComplete As Long
Dim stackIncomplete As Long
Dim stackMissing As Long
''''''''''''''''''''''''''''''''''''''''''''''''''''
stackMissing = 0
stackComplete = 0
stackIncomplete = 0
'rows represents the time intervals)
i = 2
'columns represents distance (gantries)
j = 1
'search for a hole
While (Worksheets("speed").Cells(i, j) <> "")
    While (Worksheets("speed").Cells(i, j) <> "")
        'here is jam and no control
        If (Worksheets("jam").Cells(i, j) = 1) And
(Worksheets("control").Cells(i, j) = "130") Then
            stackMissing = stackMissing + 1
            'map label, green 1
            Worksheets("mapMiss").Cells(i, j) = 1
            Worksheets("mapMiss").Cells(i, j).Interior.ColorIndex = 43
        End If
        'computes data completeness
        If (Worksheets("speed").Cells(i, j) = "255") Or
(Worksheets("speed").Cells(i, j) = "-1") Or (Worksheets("speed").Cells(i, j) =
"0") Then
            stackIncomplete = stackIncomplete + 1
            stackComplete = stackComplete + 1
        Else
            stackComplete = stackComplete + 1
        End If
    j = j + 1
    Wend
j = 1
i = i + 1
Wend
With Sheets("command")
    Set firstBlankCell = .Cells(Rows.Count, 8).End(xlUp).Offset(1, 0)
    inputEntry = firstBlankCell.Row
End With
Worksheets("command").Cells(inputEntry, 8) = stackMissing
Worksheets("command").Cells(inputEntry, 27) = stackComplete
Worksheets("command").Cells(inputEntry, 28) = stackIncomplete
End Sub

'compute mismatches and breakdowns
Sub mismatch()
Dim i As Long
Dim j As Long
Dim t As Integer
Dim d As Integer
Dim boundV As Integer
Dim boundD As Integer
Dim boundT As Integer
Dim stackMismatch As Long
Dim inputEntry As Long
Dim breakdownJamStack As Long
Dim breakdownStack2 As Long
Dim breakdownStack1 As Long
Dim stackMismatch100 As Long
Dim stackMismatch80 As Long
Dim stackMismatch60 As Long
Dim stackMismatch30 As Long
Dim firstBlankCell As Range
```

```
'''''''''''''''''''''''''''''''''''''''''''''''''''
'Resolution Power:
'=< boundV
'=< boundD (previous gantries)
'=< boundT (previous intervals)
'initiazition of Resolution Power parameters
boundV = 80
boundD = 1
boundT = 5
'''''''''''''''''''''''''''''''''''''''''''''''''''
i = 2 + boundT
j = 1 + boundD
stackMismatch = 0
stackMismatch100 = 0
stackMismatch80 = 0
stackMismatch60 = 0
stackMismatch30 = 0
stackSusp = 0
inputEntry = 0
breakdownStack2 = 0
breakdownStack1 = 0
breakdownJamStack = 0
'''''''''''''''''''''''''''''''''''''''''''''''''''
While (Worksheets("speed").Cells(i, j) <> "")
    While (Worksheets("speed").Cells(i, j) <> "")
        'here is a potential mismatch - here is control but no jam
        If (Worksheets("jam").Cells(i, j) = 0) And
(Worksheets("control").Cells(i, j) < 130) And (Worksheets("control").Cells(i, j)
> 0) Then
        'map label SUSPICIOUS, yellowish 0
            Worksheets("mapMism").Cells(i, j) = 0
            Worksheets("mapMism").Cells(i, j).Interior.ColorIndex = 36
        'clarify there is potential jam situation then this is not a mismatch
            For d = 0 To boundD
                If (Worksheets("speed").Cells(i, j - d) <= boundV) And
(Worksheets("speed").Cells(i - t, j) > 0) Then
                    Exit For
                End If
            Next d
            For t = 1 To boundT
                If (Worksheets("speed").Cells(i - t, j) <= boundV) And
(Worksheets("speed").Cells(i - t, j) > 0) Then
                    Exit For
                End If
            Next t
            If (d <> boundD + 1) Or (t <> boundT + 1) Then
                stackSusp = stackSusp + 1
            Else
                stackMismatch = stackMismatch + 1
                'map label MISMATCH,purpe 1
                Worksheets("mapMism").Cells(i, j) = 1
                Worksheets("mapMism").Cells(i, j).Interior.ColorIndex = 26
                'investigate a Mismatch
                If (Worksheets("control").Cells(i, j) = 100) Then
                    stackMismatch100 = stackMismatch100 + 1
                End If
                If (Worksheets("control").Cells(i, j) = 80) Then
                    stackMismatch80 = stackMismatch80 + 1
                End If
                If (Worksheets("control").Cells(i, j) = 60) Then
                    stackMismatch60 = stackMismatch60 + 1
                End If
                If (Worksheets("control").Cells(i, j) = 30) Then
                    stackMismatch30 = stackMismatch30 + 1
                End If
            End If
```

```
        End If
        'compute number of breakdowns based on Jam.csv
        If (Worksheets("jam").Cells(i, j) = "1") And (Worksheets("jam").Cells(i -
1, j) = "0") And (Worksheets("jam").Cells(i, j - 1) = "0") Then
            'this is a breakdown
            breakdownJamStack = breakdownJamStack + 1
            'map label JamBreakdown, red 1
            Worksheets("breakdown").Cells(i, j) = 1
            Worksheets("breakdown").Cells(i, j).Interior.ColorIndex = 3
        End If
        'compute number of breakdown based on the defined criteria:
        'actual speed <= 60km/h, speed drop 10km/h
        If (Worksheets("speed").Cells(i, j) <= 60) And
((Worksheets("speed").Cells(i, j) - Worksheets("speed").Cells(i - 1, j) >= 10) Or
(Worksheets("speed").Cells(i, j) - Worksheets("speed").Cells(i, j - 1) >= 10))
Then
            'this is a breakdown
            breakdownStack1 = breakdownStack1 + 1
            'map label JamBreakdown, if it same like breakdownJamStack then 12,
else  2(GREEN)
            Worksheets("breakdown").Cells(i, j) = 2
            Worksheets("breakdown").Cells(i, j).Interior.ColorIndex = 4
                If Worksheets("breakdown").Cells(i, j) = 1 Then
                    Worksheets("breakdown").Cells(i, j) = 12
                End If
        End If
        'compute number of breakdown based on the defined criteria:
        'actual speed <= 70km/h, speed drop 10 km/h
        If (Worksheets("speed").Cells(i, j) <= 70) And
((Worksheets("speed").Cells(i, j) - Worksheets("speed").Cells(i - 1, j) >= 10) Or
(Worksheets("speed").Cells(i, j) - Worksheets("speed").Cells(i, j - 1) >= 10))
Then
            'this is a breakdown
            breakdownStack2 = breakdownStack2 + 1
            'map label JamBreakdown, if it same like breakdownJamStack then 12,
else  2(light bluw)
            Worksheets("breakdown").Cells(i, j) = 3
            Worksheets("breakdown").Cells(i, j).Interior.ColorIndex = 8
            If Worksheets("breakdown").Cells(i, j) = 1 Then
                Worksheets("breakdown").Cells(i, j) = 13
            End If
            If Worksheets("breakdown").Cells(i, j) = 2 Then
                Worksheets("breakdown").Cells(i, j) = 23
            End If
            If Worksheets("breakdown").Cells(i, j) = 12 Then
                Worksheets("breakdown").Cells(i, j) = 123
            End If
        End If
        j = j + 1
    Wend
j = 1 + boundD
i = i + 1
Wend
With Sheets("command")
    Set firstBlankCell = .Cells(Rows.Count, 10).End(xlUp).Offset(1, 0)
    inputEntry = firstBlankCell.Row
End With
Worksheets("command").Cells(inputEntry, 9) = stackSusp
Worksheets("command").Cells(inputEntry, 10) = stackMismatch
Worksheets("command").Cells(inputEntry, 11) = stackMismatch100
Worksheets("command").Cells(inputEntry, 12) = stackMismatch80
Worksheets("command").Cells(inputEntry, 13) = stackMismatch60
Worksheets("command").Cells(inputEntry, 14) = stackMismatch30
Worksheets("command").Cells(inputEntry, 42) = breakdownJamStack
Worksheets("command").Cells(inputEntry, 43) = breakdownStack1
Worksheets("command").Cells(inputEntry, 44) = breakdownStack2
```

```
End Sub

'speed reduction time-relevance criterion
Sub time()
Dim i As Long
Dim j As Long
Dim stackDt1Poor As Long
Dim stackDt1Fair As Long
Dim stackDt1Excel As Long
Dim stackDt2Poor As Long
Dim stackDt2Fair As Long
Dim stackDt2Excel As Long
Dim inputEntry As Long
Dim switchJam As Integer
Dim period As Integer
Dim t As Integer
Dim firstBlankCell As Range
''''''''''''''''''''''''''''''''''''''''''''''''''''
period = 0
stackDt1Poor = 0
stackDt1Fair = 0
stackDt1Excel = 0
stackDt2Poor = 0
stackDt2Fair = 0
stackDt2Excel = 0
i = 8
j = 1
switchJam = 0
''''''''''''''''''''''''''''''''''''''''''''''''''''
'distance is fixed, searching over time
While (j < 115)
    'searching over time
    While (i < 1437)
    'search for the first mutual point of congestion and control
        If (switchJam = 0) And (Worksheets("jam").Cells(i, j) = 1) And
(Worksheets("control").Cells(i, j) < 130) Then
        'apply the STSF time relevant rules:
        'excelent(rank3)....dT1= 5:00 - 3:01 min, dT2 = 0:00 - 2:00 min
        'fair(rank2).......dT1= 3:00 - 1:01 min, dT2 = 2:01 - 3:00 min
        'poor(rank1).......dT1= >5:01, <1:00 min, dT2 = <0:00, >3:01 min
            '''''''''''''''''''''''
            '''investigating dT1'''
            '''''''''''''''''''''''
            'there is already jam > late control
            If (Worksheets("jam").Cells(i - 1, j) = "1") Then
                stackDt1Poor = stackDt1Poor + 1
                'map label MISMATCH,lightblue 1
                Worksheets("mapTime").Cells(i, j) = 1
                Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 34
            Else
            'investigating previous time intervals
                For t = 0 To 6
                    If (Worksheets("control").Cells(i - t, j) = 130) Then
                        period = t - 1
                        Exit For
                    'there is another jam within the period of control
                    ElseIf (Worksheets("jam").Cells(i - 1 - t, j) = "1") Then
                        period = t
                        Exit For
                    End If
                Next t
                If (period >= 0 And period <= 1) Or period = 6 Then
                    stackDt1Poor = stackDt1Poor + 1
                    'map label Time,lightblue 3
                    Worksheets("mapTime").Cells(i, j) = 1
                    Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 34
```

```
                ElseIf period >= 2 And period <= 3 Then
                    stackDt1Fair = stackDt1Fair + 1
                    'map label Time,blue 2
                    Worksheets("mapTime").Cells(i, j) = 2
                    Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 32
                Else
                    stackDt1Excel = stackDt1Excel + 1
                    'map label Time,darkblue 3
                    Worksheets("mapTime").Cells(i, j) = 3
                    Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 32
                End If
            End If
        switchJam = 1
        End If
    'search for the end of the control pattern
        If ((switchJam = 1) And Worksheets("jam").Cells(i + 1, j) <> "1") Then
            '''''''''''''''''''''''
            '''investigating dT2'''
            '''''''''''''''''''''''
            For t = 0 To 4
                If Worksheets("control").Cells(i + t, j) = "130" Then
                period = t - 1
                    Exit For
                'there is another jam within the period of control
                ElseIf (Worksheets("jam").Cells(i + 1 + t, j) = "1") Then
                period = t
                    Exit For
                End If
            Next t
            If period = 0 Or period = 4 Then
                stackDt2Poor = stackDt2Poor + 1
                'map label Time,lightorange 1
                Worksheets("mapTime").Cells(i, j) = 1
                Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 46
            ElseIf period = 3 Then
                stackDt2Fair = stackDt2Fair + 1
                'map label Time,orange 1
                Worksheets("mapTime").Cells(i, j) = 2
                Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 45
            Else
                stackDt2Excel = stackDt2Excel + 1
                'map label Time,darkorange 1
                Worksheets("mapTime").Cells(i, j) = 3
                Worksheets("mapTime").Cells(i, j).Interior.ColorIndex = 44
            End If
            switchJam = 0
        End If
    i = i + 1
    Wend
switchJam = 0
i = 8
j = j + 1
Wend
With Sheets("command")
    Set firstBlankCell = .Cells(Rows.Count, 2).End(xlUp).Offset(1, 0)
    inputEntry = firstBlankCell.Row
End With
'distinguish between dt1/dt2
Worksheets("command").Cells(inputEntry, 4) = stackDt1Poor
Worksheets("command").Cells(inputEntry, 3) = stackDt1Fair
Worksheets("command").Cells(inputEntry, 2) = stackDt1Excel
Worksheets("command").Cells(inputEntry + 1, 4) = stackDt2Poor
Worksheets("command").Cells(inputEntry + 1, 3) = stackDt2Fair
Worksheets("command").Cells(inputEntry + 1, 2) = stackDt2Excel
Worksheets("command").Cells(inputEntry, 5) = stackDt1Poor + stackDt1Fair +
stackDt1Excel
```

```
Worksheets("command").Cells(inputEntry + 1, 5) = stackDt2Poor + stackDt2Fair +
stackDt2Excel
End Sub

'speed reduction spatial-relevance criterion
Sub spatial()
Dim switchJam As Integer
Dim i As Long
Dim j As Long
Dim stackdD1 As Long
Dim stackdD2 As Long
Dim inputEntry As Long
Dim firstBlankCell As Range
'''''''''''''''''''''''''''''''''''''''''''''''''''
i = 2
j = 3
switchJam = 0
stackdD1 = 0
stackdD2 = 0
'''''''''''''''''''''''''''''''''''''''''''''''''''
While i < 1440
    While j < 113
    'search for the first mutual point of congestion and control
        If (switchJam = 0) And (Worksheets("jam").Cells(i, j) = "1") And
(Worksheets("control").Cells(i, j) < 130) Then
        'apply the spatial rules for preceding gantries based on the speed
reduction at the point i,j
        'apply the STSF spatial relevant rules:
        '''''''''''''''''''''''''''''''''''''''''''
        'velocity reduction  120km/h   80km/h  60km/h
        'preceding gantries     0       0-1     1
        'following gantries     0       0       0
        '''''''''''''''''''''''''''''''''''''''''''
        'assume speed reduction consistency
            'control is late
            If (Worksheets("jam").Cells(i, j - 1) = "1") And
(Worksheets("control").Cells(i, j - 1) = "130") Then
                stackdD1 = stackdD1 + 1
                'map label Spatial,dark grey 1
                Worksheets("mapSpatial").Cells(i, j) = 1
                Worksheets("mapSpatial").Cells(i, j).Interior.ColorIndex = 56
            'investigating preceding gantries regarding the speed reduction at
i,j
            '30 and 60 km/h have same conditions determining stackdD1
            ElseIf Worksheets("control").Cells(i, j) = "60" Or
Worksheets("control").Cells(i, j) = "30" Then
                If ((Worksheets("control").Cells(i, j - 2) < 130) And
(Worksheets("jam").Cells(i, j - 2) <> "1")) Or (Worksheets("control").Cells(i, j
- 1) <= 60) Or (Worksheets("control").Cells(i, j - 1) = "130") Then
                    stackdD1 = stackdD1 + 1
                    'map label Spatial,dark grey 1
                    Worksheets("mapSpatial").Cells(i, j) = 1
                    Worksheets("mapSpatial").Cells(i, j).Interior.ColorIndex = 56
                End If
            ElseIf Worksheets("control").Cells(i, j) = "80" Then
                If (Worksheets("control").Cells(i, j - 2) < 130) Then
                    stackdD1 = stackdD1 + 1
                    'map label Spatial,dark grey 1
                    Worksheets("mapSpatial").Cells(i, j) = 1
                    Worksheets("mapSpatial").Cells(i, j).Interior.ColorIndex = 56
                End If
            'speed reduction on the gantry i,j is 100
            ElseIf (Worksheets("control").Cells(i, j - 1) < 130) Then
                    stackdD1 = stackdD1 + 1
                    'map label Spatial,dark grey 1
                    Worksheets("mapSpatial").Cells(i, j) = 1
```

```
                    Worksheets("mapSpatial").Cells(i, j).Interior.ColorIndex = 56
                End If
                'congestion indicator - congestion ON
                switchJam = 1
            End If
            'this is the end of the congestion, apply the rule for the following
gantries
            If (switchJam = 1) And (Worksheets("jam").Cells(i, j + 1) <> "1") Then
                If (Worksheets("control").Cells(i, j) = "130") Or
((Worksheets("control").Cells(i, j + 1) < 130) And (Worksheets("jam").Cells(i, j
+ 1) <> "1")) And (Worksheets("jam").Cells(i, j + 2) <> "1") Then
                    stackdD2 = stackdD2 + 1
                    'map label Spatial,light grey 2
                    Worksheets("mapSpatial").Cells(i, j) = 2
                    Worksheets("mapSpatial").Cells(i, j).Interior.ColorIndex = 15
                End If
            switchJam = 0
            End If
        j = j + 1
        Wend
switchJam = 0
j = 3
i = i + 1
Wend
With Sheets("command")
    Set firstBlankCell = .Cells(Rows.Count, 7).End(xlUp).Offset(1, 0)
    inputEntry = firstBlankCell.Row
End With
Worksheets("command").Cells(inputEntry, 7) = stackdD1
Worksheets("command").Cells(inputEntry + 1, 7) = stackdD2
End Sub

'DR and FAR
Sub rates()
Dim i As Long
Dim j As Long
Dim sumJamExtended As Long
Dim sumInter As Long
Dim sumControl As Long
Dim section As Long
Dim inter100 As Long
Dim inter80 As Long
Dim inter60 As Long
Dim inter30 As Long
Dim speedR100 As Double
Dim speedR80 As Double
Dim speedR60 As Double
Dim speedR30 As Double
Dim weight1 As Long
Dim weight2 As Long
Dim stackJamSection As Double
Dim dT1 As Integer
Dim dT2 As Integer
Dim dL1 As Integer
Dim dL2 As Integer
Dim DR As Double
Dim DR100 As Double
Dim DR80 As Double
Dim DR60 As Double
Dim DR30 As Double
Dim FAR As Double
Dim FAR100 As Double
Dim FAR80 As Double
Dim FAR60 As Double
Dim FAR30 As Double
Dim DRweight As Double
```

```
Dim FARweight As Double
Dim inputEntry As Long
Dim firstBlankCell As Range
Worksheets("inter").Cells.Clear
Worksheets("jamExtended").Cells.Clear
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'dT1 time between the beginning of jam and the beginning of jam*(extension)
'dT2 time between the end of jam and the end of jam*(extension)
'dL1 distance between the beginning of jam and the beginning of jam*(extension)
'dL2 distance between the end of jam and the end of jam*(extension)
dT1 = 5
dT2 = 0
dL1 = 1
dL2 = 0
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
section = 5
i = 2
j = 1
sumControl = 0
inter60 = 0
speedR60 = 0
inter80 = 0
speedR80 = 0
inter100 = 0
speedR100 = 0
stackJamSection = 0
sumJamExtended = 0
weight1 = 2000
weight2 = 5000
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
' search for the matrix c_extended'''''''''''''''''''''''''
'vertical extension
While Worksheets("speed").Cells(i, j) <> ""
    While Worksheets("speed").Cells(i + dT1 + dT2, j) <> ""
       If Worksheets("jam").Cells(i + dT1, j) = 1 Then
            For x = 0 To dT1
                Worksheets("jamExtended").Cells(i + x, j) = 1
                    For y = 0 To dT2
                        Worksheets("jamExtended").Cells(i + dT1 + y, j) = 1
                    Next y
            Next x
        End If
    i = i + 1
    Wend
i = 2
j = j + 1
Wend
i = 2
j = 1
'horizontal extension
While Worksheets("speed").Cells(i, j) <> ""
    While Worksheets("speed").Cells(i, j + dL1 + dL2) <> ""
       If Worksheets("jam").Cells(i, j + dL1) = 1 Then
            For x = 0 To dL1
                Worksheets("jamExtended").Cells(i, j + x) = 1
                    For y = 0 To dL2
                        Worksheets("jamExtended").Cells(i, j + dL1 + y) = 1
                    Next y
            Next x
        End If
    j = j + 1
    Wend
j = 1
i = i + 1
Wend
' search for the matrix intersection
```

```
i = 2
j = 1
While Worksheets("speed").Cells(i, j) <> ""
    While Worksheets("speed").Cells(i, j) <> ""
        If (Worksheets("jamExtended").Cells(i, j) = 1) And
(Worksheets("control").Cells(i, j) < 130) And (Worksheets("control").Cells(i, j)
> 1) Then
            Worksheets("inter").Cells(i, j) = 1
        End If
    i = i + 1
    Wend
i = 2
j = j + 1
Wend
'count  the area sizes
i = 2
j = 1
While Worksheets("speed").Cells(i, j) <> ""
    While Worksheets("speed").Cells(i, j) <> ""
        'area size of R
        If (Worksheets("control").Cells(i, j) < 130) And
(Worksheets("control").Cells(i, j) > 1) Then
            sumControl = sumControl + 1
        End If
        'area size of I
        If Worksheets("inter").Cells(i, j) = 1 Then
            sumInter = sumInter + 1
        End If
        'area size of C'
        If Worksheets("jamExtended").Cells(i, j) = 1 Then
            sumJamExtended = sumJamExtended + 1
        End If
    i = i + 1
    Wend
i = 2
j = j + 1
Wend
'count the DR and FAR based on the SPEED REDUCTION value
'DR100,80,60
'FAR100,80,60
'the investigating section (detector,gantry)
i = 2
j = 1
While Worksheets("speed").Cells(i, j) <> ""
    While Worksheets("speed").Cells(i, j) <> ""
        'finding the mutual point
        If (Worksheets("control").Cells(i, j) < 130) And
(Worksheets("control").Cells(i, j) > 1) And (Worksheets("jamExtended").Cells(i,
j) = 1) Then
            'distinguish between the certain value of speed reduction
            If Worksheets("control").Cells(i, j) = 100 Then
                inter100 = inter100 + 1
                speedR100 = speedR100 + 1
            ElseIf Worksheets("control").Cells(i, j) = 80 Then
                inter80 = inter80 + 1
                speedR80 = speedR80 + 1
            ElseIf Worksheets("control").Cells(i, j) = 60 Then
                inter60 = inter60 + 1
                speedR60 = speedR60 + 1
            ElseIf Worksheets("control").Cells(i, j) = 30 Then
                inter30 = inter30 + 1
                speedR30 = speedR30 + 1
            End If
        End If
        'count the areas C' pieces  which are not covered by speed reduction
```

```
        If (Worksheets("control").Cells(i, j) = 130) And
(Worksheets("jamExtended").Cells(i, j) = "1") Then
            stackJamSection = stackJamSection + 1
        End If
        'count the pieces areas R which are outside the C'
        If (Worksheets("control").Cells(i, j) < 130) And
(Worksheets("control").Cells(i, j) > 1) And (Worksheets("jamExtended").Cells(i,
j) <> 1) Then
            If Worksheets("control").Cells(i, j) = 100 Then
                speedR100 = speedR100 + 1
            ElseIf Worksheets("control").Cells(i, j) = 80 Then
                speedR80 = speedR80 + 1
            ElseIf Worksheets("control").Cells(i, j) = 60 Then
                speedR60 = speedR60 + 1
            ElseIf Worksheets("control").Cells(i, j) = 30 Then
                speedR30 = speedR30 + 1
            End If
        End If
    i = i + 1
    Wend
i = 2
j = j + 1
Wend
'compute DR
If sumJamExtended = 0 Then
    DR = 0
Else
    DR = sumInter / sumJamExtended
End If
If (inter100 + inter80 + inter60 + inter30) = 0 Then
    DR100 = 0
Else
    DR100 = (inter100 + inter80 + inter60 + inter30) / (inter100 + inter80 +
inter60 + inter30 + stackJamSection)
End If
If (inter80 + inter60 + inter30) = 0 Then
    DR80 = 0
Else
    DR80 = (inter80 + inter60 + inter30) / (inter80 + inter60 + inter30 +
stackJamSection)
End If
If (inter60 + inter30) = 0 Then
    DR60 = 0
Else
    DR60 = (inter60 + inter30) / (inter60 + inter30 + stackJamSection)
End If
If inter30 = 0 Then
    DR30 = 0
Else
    DR30 = inter30 / (inter30 + stackJamSection)
End If
'compute FAR
If sumControl = 0 Then
    FAR = 0
Else
    FAR = 1 - (sumInter / sumControl)
End If
If speedR30 = 0 Then
    dummy = 1
End If
FAR30 = 1 - (inter30 / (speedR30 + dummy))
If inter30 = 0 Then
    FAR30 = 0
    dummy = 0
End If
If (speedR60 + speedR30) = 0 Then
```

```
     dummy = 1
End If
FAR60 = 1 - ((inter60 + inter30) / (speedR60 + speedR30 + dummy))
If (inter60 + inter30) = 0 Then
     FAR60 = 0
     dummy = 0
End If
If (speedR80 + speedR60 + speedR30) = 0 Then
     dummy = 1
End If
FAR80 = 1 - ((inter80 + inter60 + inter30) / (speedR80 + speedR60 + speedR30 +
dummy))
If (inter80 + inter60 + inter30) = 0 Then
     FAR80 = 0
     dummy = 0
End If
If (speedR100 + speedR80 + speedR60 + speedR30) = 0 Then
     dummy = 1
End If
FAR100 = 1 - ((inter100 + inter80 + inter60 + inter30) / (speedR100 + speedR80 +
speedR60 + speedR30 + dummy))
If (inter100 + inter80 + inter60 + inter30) = 0 Then
     FAR100 = 0
     dummy = 0
End If
'weights
If (sumJamExtended <= weight1) Then
     DRweight = DR * 10
     FARweight = FAR * 10
ElseIf (sumJamExtended <= weight2) Then
     DRweight = DR * 30
     FARweight = FAR * 30
ElseIf (sumJamExtended > weight2) Then
     DRweight = DR * 60
     FARweight = FAR * 60
End If
With Sheets("command")
     Set firstBlankCell = .Cells(Rows.Count, 15).End(xlUp).Offset(1, 0)
     inputEntry = firstBlankCell.Row
End With
Worksheets("command").Cells(inputEntry, 15) = FAR
Worksheets("command").Cells(inputEntry, 16) = FARweight
Worksheets("command").Cells(inputEntry, 17) = FAR100
Worksheets("command").Cells(inputEntry, 18) = FAR80
Worksheets("command").Cells(inputEntry, 19) = FAR60
Worksheets("command").Cells(inputEntry, 20) = FAR30
Worksheets("command").Cells(inputEntry, 21) = DR
Worksheets("command").Cells(inputEntry, 22) = DRweight
Worksheets("command").Cells(inputEntry, 23) = DR100
Worksheets("command").Cells(inputEntry, 24) = DR80
Worksheets("command").Cells(inputEntry, 25) = DR60
Worksheets("command").Cells(inputEntry, 26) = DR30
Worksheets("command").Cells(inputEntry, 30) = sumJamExtended
Worksheets("command").Cells(inputEntry, 31) = sumInter
Worksheets("command").Cells(inputEntry, 32) = sumControl
Worksheets("command").Cells(inputEntry, 33) = inter100
Worksheets("command").Cells(inputEntry, 34) = inter80
Worksheets("command").Cells(inputEntry, 35) = inter60
Worksheets("command").Cells(inputEntry, 36) = inter30
Worksheets("command").Cells(inputEntry, 37) = speedR100
Worksheets("command").Cells(inputEntry, 38) = speedR80
Worksheets("command").Cells(inputEntry, 39) = speedR60
Worksheets("command").Cells(inputEntry, 40) = speedR30
Worksheets("command").Cells(inputEntry, 41) = stackJamSection
End Sub
```

APPENDIX B: TRAFFIC BREAKDOWN MANUAL ANALYSIS

The three tables below presents the manual evaluation of traffic breakdown recognition for AIX-ProB strategy. Totally the 15 incidents were manually analyzed. The author found 6 as incorrectly and 9 as correctly recognized. The decision has been done based on the relevant speed values, intensity of their changes (speed drops) and changes severity. Additionally, the author took into account the corresponding flow rate values.

Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]	Q [veh/15min]	v [km/h]
1 824	83	2 400	83	1 764	91	2 652	86	3 492	69	2 560	87	2 400	85	3 052	77
1 908	79	2 377	89	1 848	89	2 644	84	3 480	71	2 520	90	2 356	87	3 136	75
1 900	74	2 434	87	1 836	87	2 580	89	3 436	70	2 486	90	2 364	84	3 184	80
1 944	73	2 400	86	1 796	85	2 584	89	3 452	68	2 520	67	2 460	84	3 232	80
1 924	75	2 443	75	1 844	91	2 568	86	3 540	72	2 464	65	2 448	90	3 248	67
1 984	79	2 550	71	1 832	92	2 544	87	3 528	70	2 503	65	2 468	85	3 264	81
2 012	79	2 584	87	1 912	86	2 508	95	3 512	72	2 559	63	2 468	90	3 304	84
2 020	79	2 580	86	1 912	89	2 516	87	3 540	71	2 589	65	2 452	86	3 376	81
1 936	77	2 556	90	1 964	82	2 452	88	3 480	63	2 516	79	2 460	84	3 324	88
1 856	83	2 592	85	1 996	84	2 448	85	3 496	66	2 443	78	2 424	89	3 328	82
1 828	84	2 660	84	1 980	89	2 420	88	3 476	67	2 409	77	2 468	88	3 328	74
1 840	74	2 692	79	2 000	79	2 352	86	3 460	57	2 464	62	2 504	76	3 336	74
1 932	72	2 724	65	1 992	87	2 368	84	3 460	64	2 511	53	2 468	85	3 316	72
1 940	70	2 788	64	2 052	69	2 432	70	3 524	64	2 490	68	2 564	69	3 348	71
1 976	59	2 880	69	2 096	86	2 484	61	3 488	71	2 464	85	2 524	94	3 400	70
1 992	72	2 836	72	2 048	98	2 556	83	3 496	71	2 451	81	2 524	86	3 416	66
1 952	85	2 896	85	1 968	89	2 600	83	3 480	70	2 421	92	2 472	91	3 372	68
1 924	85	2 828	88	1 984	88	2 616	87	3 460	68	2 400	83	2 440	88	3 336	68
1 864	78	2 908	72	1 996	93	2 636	86	3 456	60	2 348	90	2 432	82	3 296	66
1 908	72	2 940	74	1 992	91	2 632	87	3 400	60	2 404	88	2 516	83	3 264	76
1 960	84	2 940	74	2 016	87	2 664	61	3 420	63	2 380	90	2 532	81	3 232	76

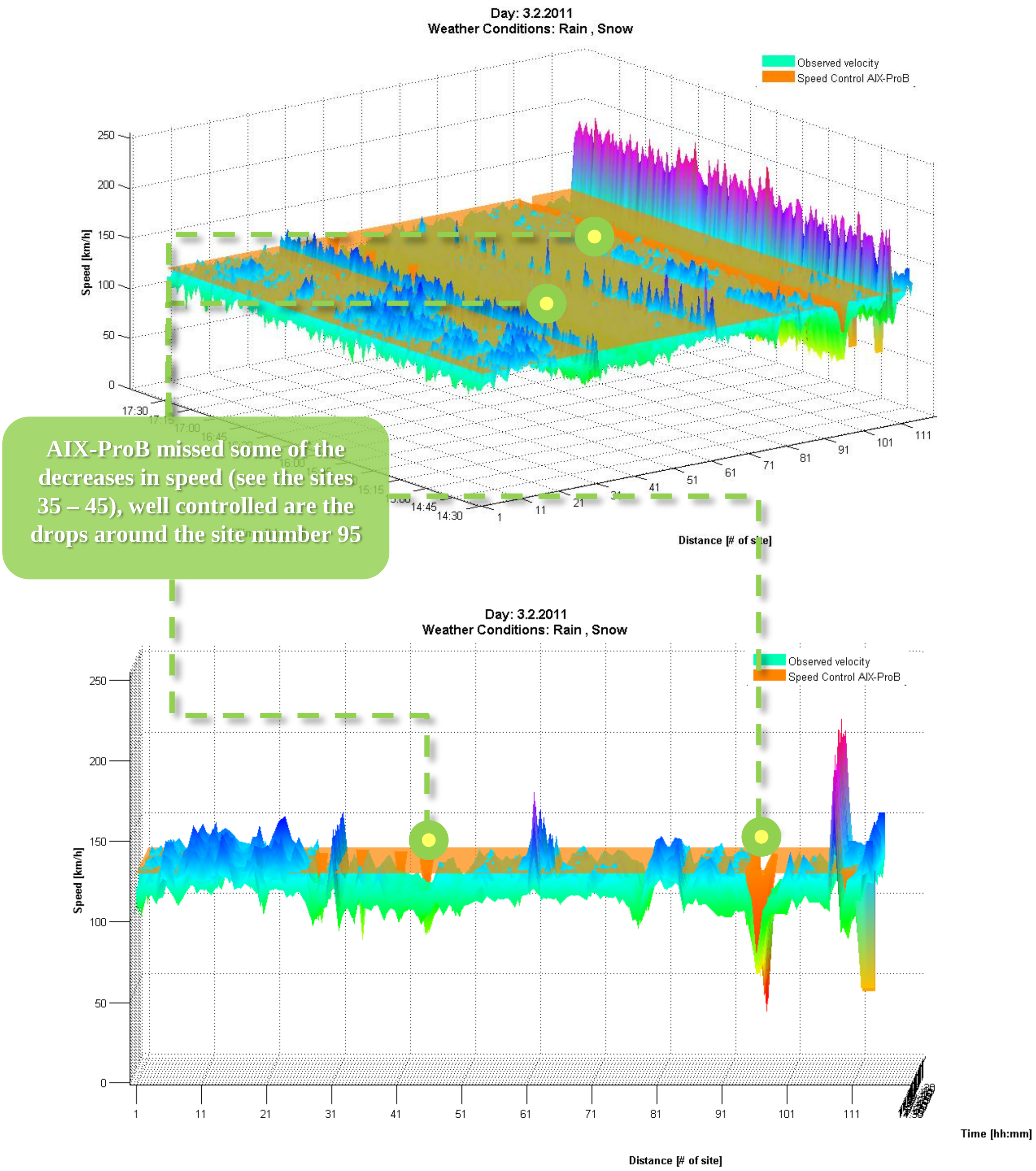
Q [veh/15mir	v [km/h]	Q [veh/15mir	v [km/h]	Q [veh/15mir	v [km/h]	Q [veh/15mir	v [km/h]	Q [veh/15mir	v [km/h]	Q [veh/15mir	v [km/h]	Q [veh/15mir	v [km/h]
2 568	79	2 628	88	2 712	92	2 232	90	2 600	75	2 544	84	3 464	69
2 504	79	2 616	84	2 764	82	2 312	86	2 656	79	2 460	85	3 472	60
2 468	79	2 628	85	2 744	87	2 404	78	2 608	87	2 508	67	3 476	65
2 456	78	2 668	84	2 792	77	2 312	89	2 576	85	2 476	74	3 492	66
2 428	84	2 728	83	2 752	80	2 268	83	2 572	78	2 492	73	3 516	69
2 416	81	2 776	87	2 788	86	2 184	87	2 632	85	2 520	77	3 508	65
2 472	73	2 740	82	2 824	87	2 236	85	2 648	78	2 540	79	3 520	59
2 512	80	2 688	94	2 808	81	2 252	86	2 616	80	2 524	81	3 536	62
2 480	82	2 696	88	2 820	90	2 332	92	2 624	85	2 528	79	3 500	59
2 508	89	2 740	88	2 792	80	2 392	88	2 676	79	2 492	72	3 520	53
2 520	88	2 752	89	2 744	82	2 424	91	2 656	83	2 452	82	3 516	68
2 548	72	2 776	71	2 804	64	2 480	76	2 696	72	2 516	68	3 496	55
2 588	64	2 760	57	2 828	63	2 524	69	2 744	67	2 552	56	3 504	58
2 592	69	2 888	63	2 896	61	2 608	68	2 784	66	2 512	66	3 512	64
2 548	85	2 948	68	2 916	72	2 660	83	2 804	76	2 540	73	3 516	65
2 524	85	2 904	85	3 028	65	2 732	84	2 876	77	2 548	72	3 588	57
2 572	82	2 880	88	3 020	65	2 784	77	2 944	69	2 668	67	3 604	60
2 576	75	2 868	83	3 060	71	2 700	81	2 988	66	2 612	74	3 612	67
2 604	74	2 920	76	3 056	78	2 772	96	3 064	82	2 652	86	3 564	71
2 592	75	2 844	85	3 124	79	2 748	92	3 052	81	2 644	83	3 552	61
2 580	88	2 876	75	3 140	77	2 780	90	3 076	85	2 680	83	3 512	66

Traffic breakdown is recognized correctly — Traffic breakdown is recognized incorrectly

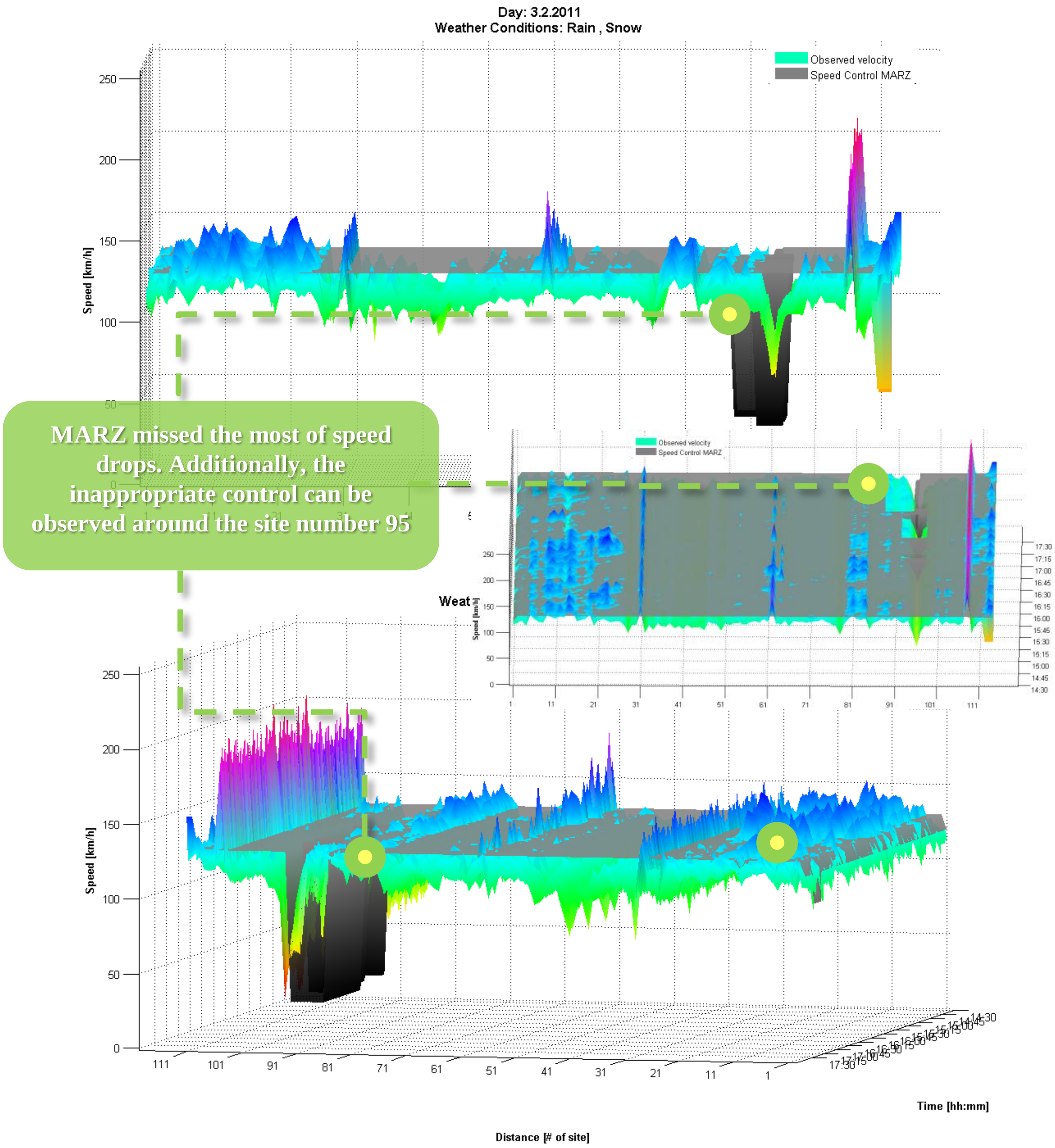
Appendix B: Manual analysis of Traffic Breakdown Recognition for AIX-Prob Strategy

APPENDIX C: STSF VISUALIZATIONS

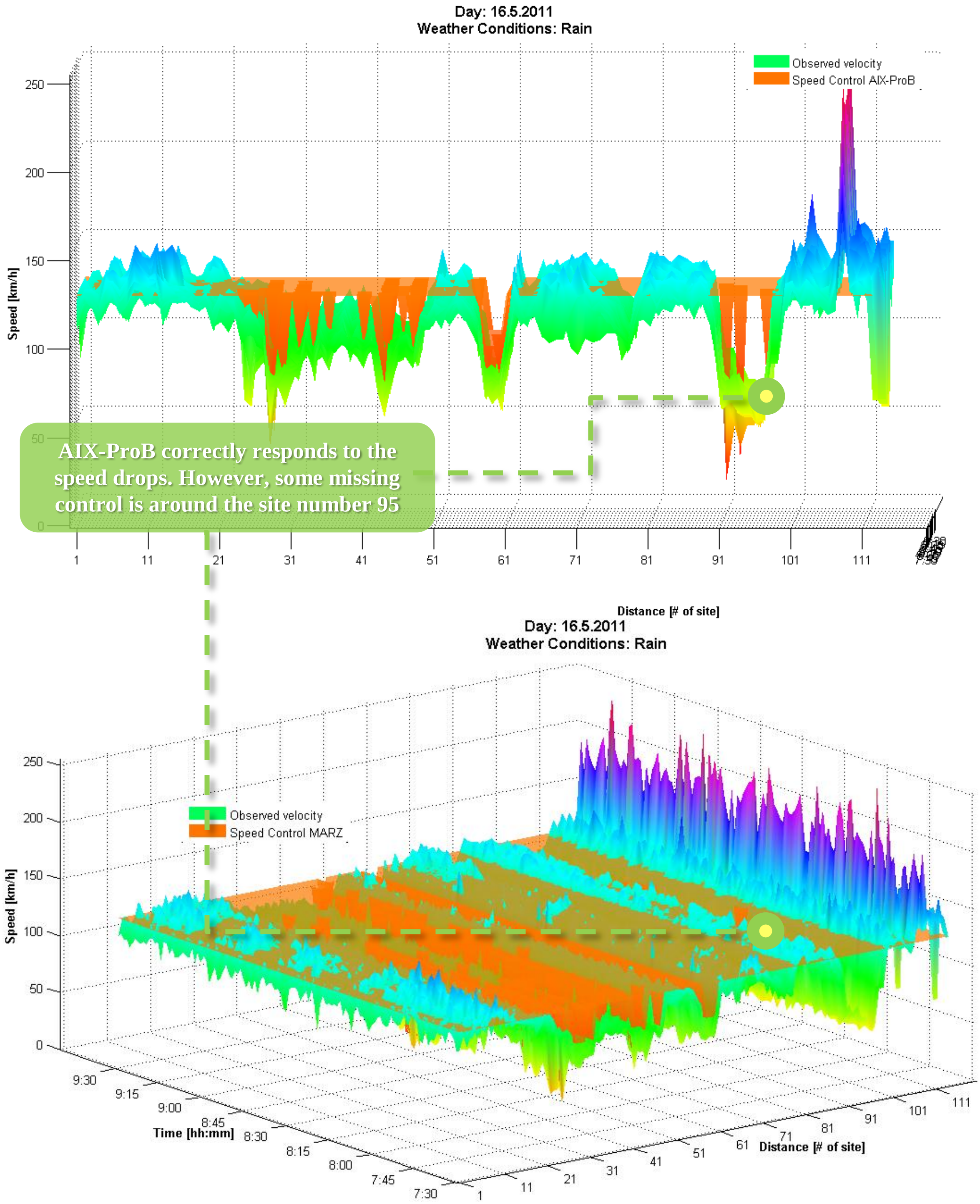
The following STSF visualizations document the most of randomly chosen days (presented in 5.5) when the unfavorable environmental conditions were reported.



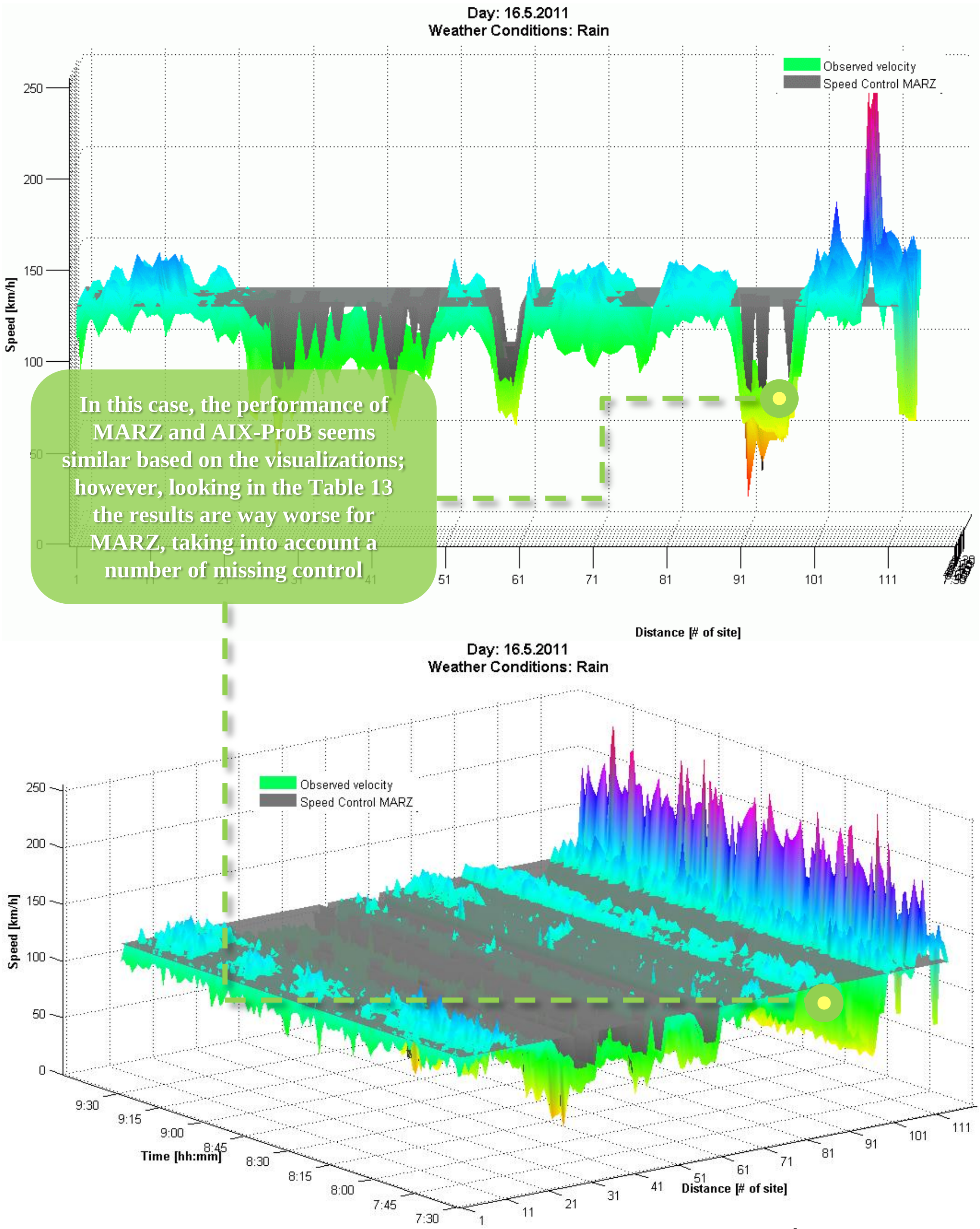
Appendix C 1: STSF visualization for AIX-ProB on February 3rd



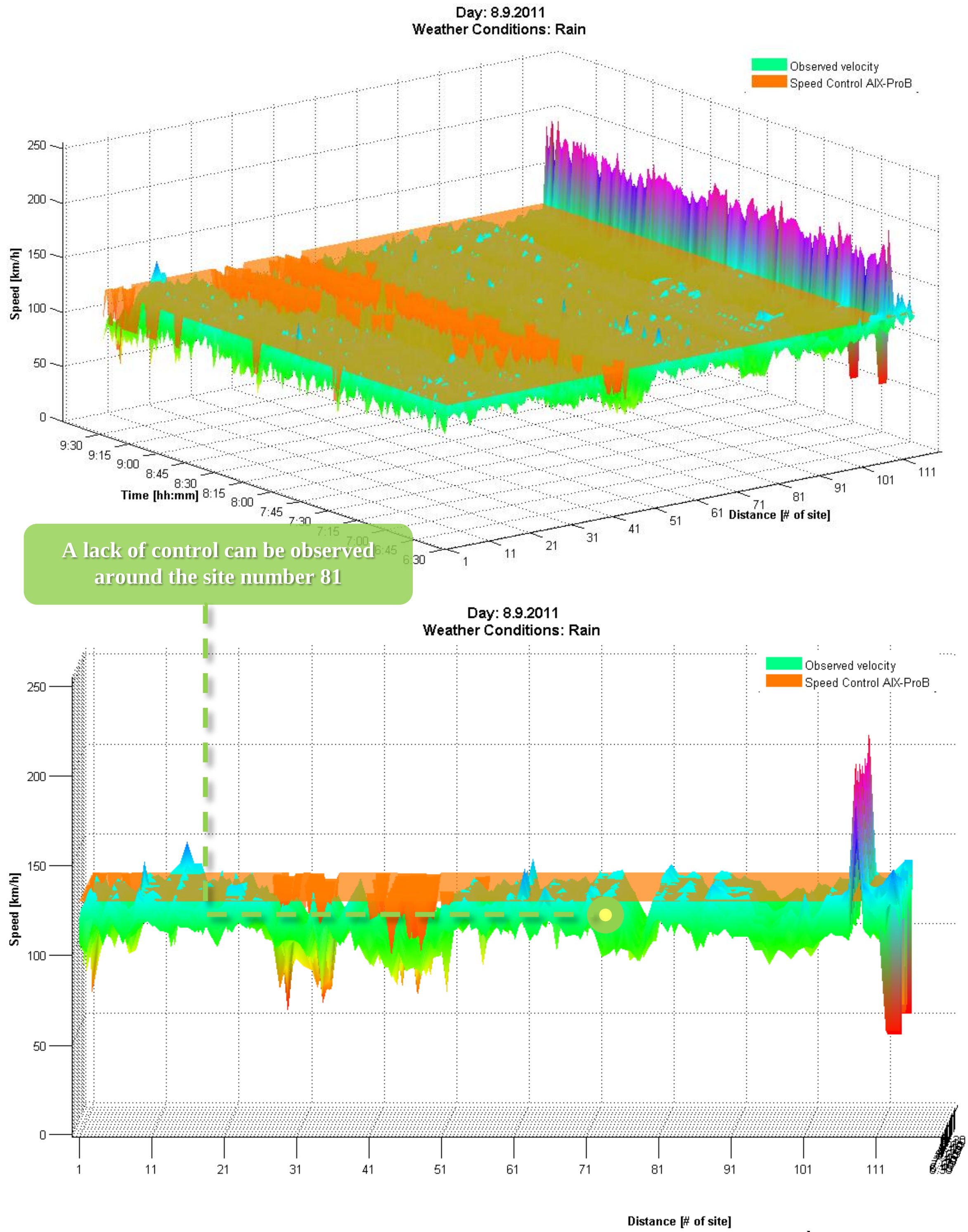
Appendix C 2: STSF visualization for MARZ on February 3rd



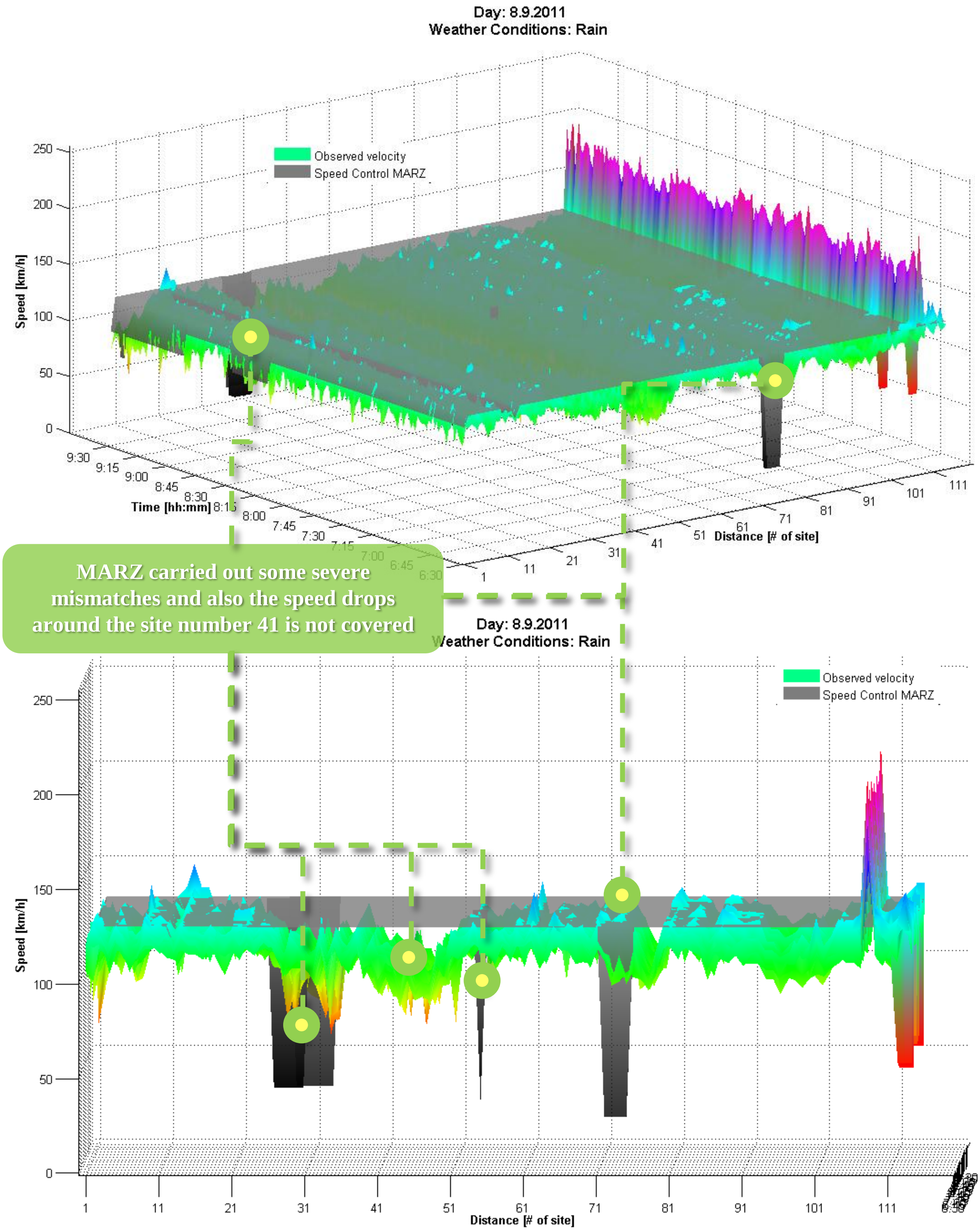
Appendix C 3: STSF visualization for AIX-ProB on May 16th



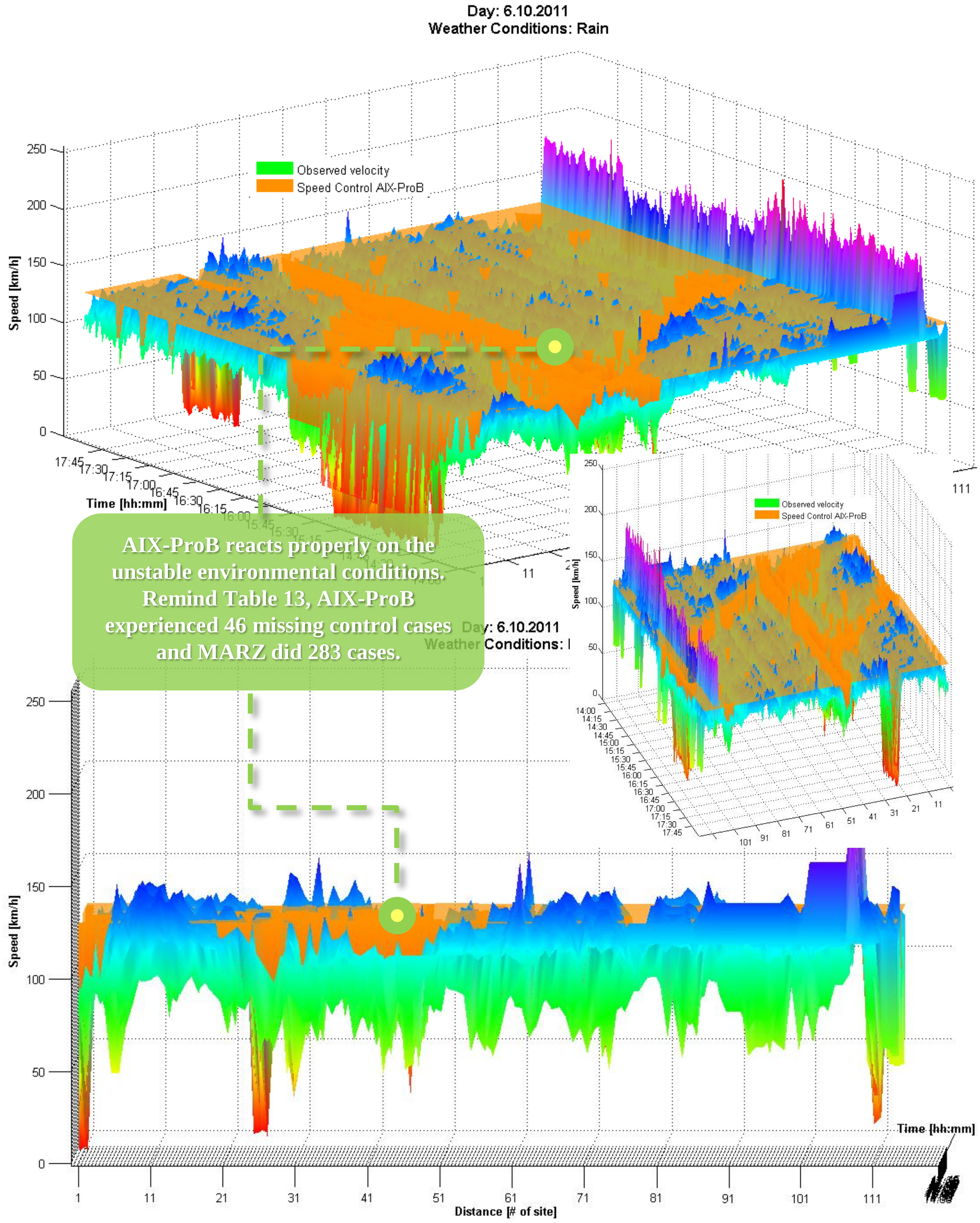
Appendix C 4: STSF visualization for MARZ on May 16th



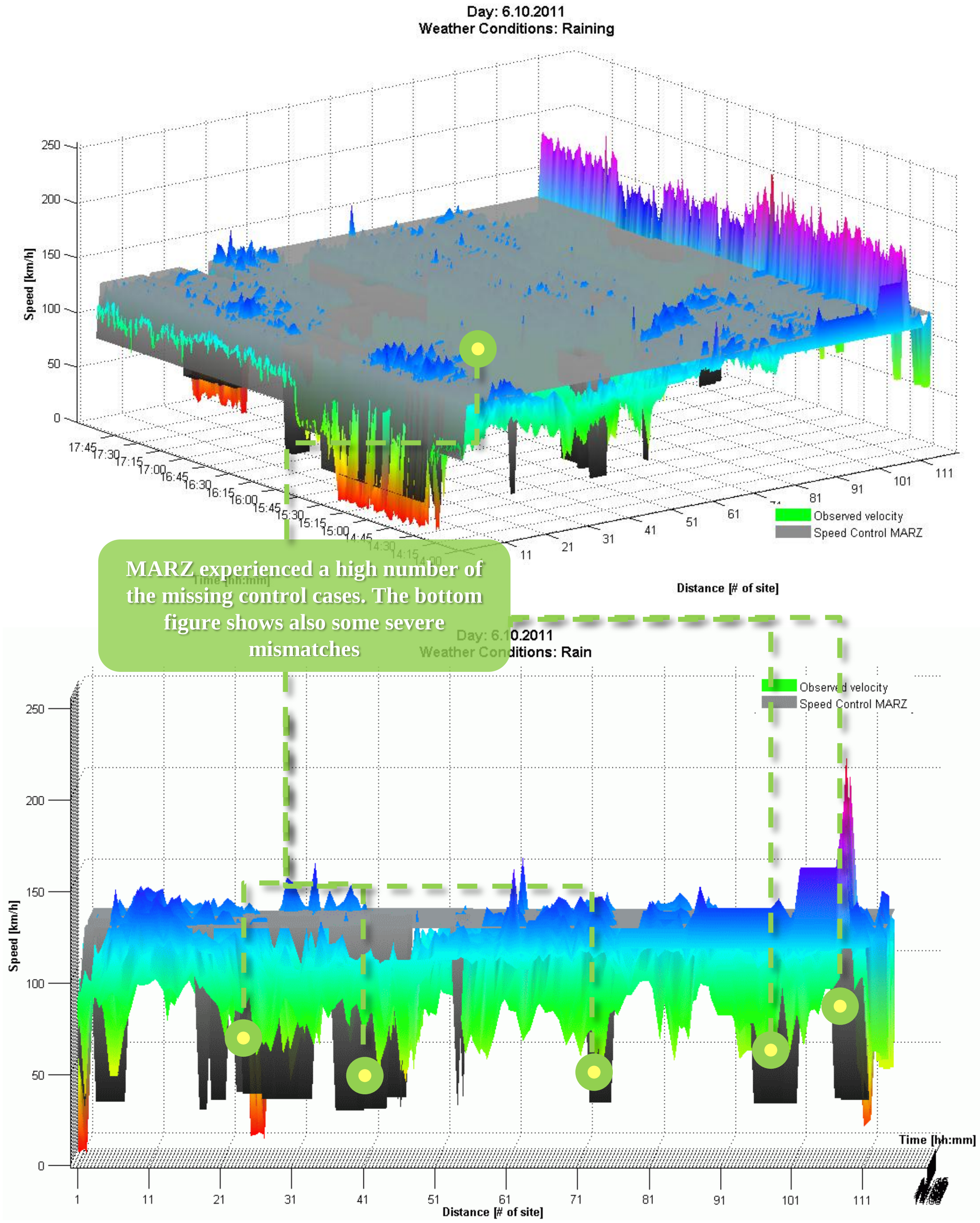
Appendix C 5: STSF visualization for MARZ on September 9th



Appendix C 6: STSF visualization for MARZ on September 9th



Appendix C 7: STSF visualization for AIX-ProB on August 10th



Appendix C 8: STSF visualization for MARZ on August 10th