Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Classification of traffic jams on alpine motorways

Bartosz Bursa[a]*, Nemanja Gajic[a], Markus Mailer[a]

[a] *Unit for Intelligent Transport Systems, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria*

Abstract

First, we briefly summarize the state of research in traffic congestion and existing approaches towards jam classification. We describe the assumptions of the adaptive smoothing method used for processing the empirical data. We present the results of our analysis of the spatiotemporal dynamics of traffic flow on the A12 and A13 motorways in Austria in 2016. Next, we discuss the outcomes for the A12 in detail and compare them with those from the A9 motorway in Germany to see if there are specific patterns due to specific conditions on alpine motorways. We postulate that the situation on the A12 is a result of local traffic overlapping with high seasonal tourist traffic waves, the density of bottlenecks and lack of alternative routes. We also describe technical and methodological problems that we have encountered during the work, particularly regarding the A13. Finally, we propose solutions to overcome these issues and give even more precise data about the exact reasons for each of the congestion types. We also outline our further research plans in this area.

Keywords: traffic jam; traffic congestion; traffic waves; traffic shockwaves; classification of traffic jams; traffic patterns; alpine region; tourist traffic

* Corresponding author. Tel.: +43 512 507-62405; Fax: +43 512 507-62498.
E-mail address: bartosz.bursa@uibk.ac.at

1. Introduction

1.1. Background and motivation

Traffic on alpine motorways is characterized by extensive seasonal variability in volumes caused by tourism, recreational traffic interfering with local traffic and considerable (truck) transit. Alpine transport systems provide only few viable alternative routes and decision points for routing are far distant from potential bottlenecks or incident locations. This results in frequent and extensive traffic jams on some specific days of the year.

Traffic flow stability and reliability of forecasted journey times (respective estimated time of arrival ETA) determine the level of service in the transport network. Disturbances in stable performance result in time losses as well as financial and social costs on the part of the user and operator. In order to reduce the probability of traffic jams occurring and introduce appropriate ITS solutions, knowledge about the specific characteristics of traffic flow and its attributes in a particular area of the network is crucial.

Thus, the major aim of this study is to identify specific flow patterns, disturbances and their reasons, as well as critical locations on the typical alpine motorways of the A12 and A13 in Austria, which are part of the Trans-European corridor from Scandinavia to the Mediterranean. Such an extensive analysis of traffic patterns on the whole length (85 km) of the A12 in both directions has not been performed so far.

The study has been carried out in cooperation with the consultancy TRANSVER which has developed a tool to analyze and display traffic conditions, and the Austrian motorway administration ASFiNAG which provided the data required. Processing cross-sectional count data from numerous locations on the A12 and A13 using algorithms based on the adaptive smoothing method (ASM) allowed us to reconstruct the traffic situation, obtain space-time-velocity diagrams of traffic flows and analyze propagation characteristics, differences, and commonalities of traffic flow disturbances. The areas notorious for congestion were successfully detected and jam types were identified according to the classification from (TRANSVER GmbH, 2010).

1.2. Organization of this paper

This paper starts with an abstract and short introduction into the research subject. In section 2, we briefly describe the two major competitive scientific approaches towards congestion classification and the approach of BMW and the consultancy TRANSVER that was selected for this study. We also illustrate the assumptions of the adaptive smoothing method (ASM) that was applied to our dataset and characterize our measurement site and the data used. Section 3 of this paper presents the findings of our research. An overview of the general traffic situation along the A12 and A13 motorways is provided along with a detailed evaluation of congestion patterns on the A12, broken down into segments and periods. This section also includes an analysis of untypical issues encountered during the research. Finally, in section 4, we summarize our findings and make conclusions, as well as discuss necessary future work and possible further research steps.

2. Methodology

2.1. Existing approaches in traffic congestion research

2.1.1. Kerner's approach

The three-phase traffic theory was mainly developed and presented by Kerner and Rehborn in 1996. The major hypothesis of this theory is that a synchronized flow state covers a two-dimensional region in the flow-density diagram, which means that for a given velocity, there is an infinite number of possible densities within a certain range, and for a given density, there is an infinite number of possible velocities within a certain range (Kerner, 2004).

There are three major traffic phases specified in Kerner's theory (Kerner & Rehborn, 1996):
- Free flow (F)
- Synchronized flow (S)

- Wide moving jam (J)

Kerner defines the wide moving jam (J) as a moving jam that propagates upstream with a constant mean velocity. It means that its downstream front moves undisturbed through other traffic states or bottlenecks in the upstream direction. Contrary to the wide moving jam, in the synchronized flow (S) the downstream front does not relocate at a constant speed and is usually fixed to a certain location (bottleneck). In other cases, we are dealing with the free flow (F), i.e. a state in which vehicles move undisrupted at their desired speeds.

Since the division of congested traffic states into only two categories, (J) and (S), does not always allow an accurate classification of traffic phenomena based on real macroscopic data, Kerner introduces some additional terms (Kerner, 2009). This is for example a narrow jam being a subtype of synchronized flow (S) or a mega-wide moving jam. Kerner defines a synchronized flow pattern (SP) as a congested pattern, which consists only of the synchronized flow phase (S). A combination of a wide moving jam (J) and synchronized flow phase (S) is called a general pattern (GP). There are three types of synchronized flow patterns (SP) differing in behavior at their upstream and downstream fronts:

- Localized SP (LSP)
- Widening SP (WSP)
- Moving SP (MSP)

In addition, Kerner distinguishes three further kinds of state in the synchronized flow (S) (Kerner & Rehborn, 1996) with the following features:

- Stationary and homogeneous states – both the average speed and the flow rate are stationary.
- Homogeneous-in-speed states – only the average vehicle speed is stationary.
- Non-stationary and non-homogeneous states.

Based on the three-phase traffic theory, two models for the automatic recognition and tracking of congested spatiotemporal flow patterns on freeways have been developed by Kerner et al. (2004). Both models FOTO (*Forecasting of Traffic Objects*) and ASDA (*Automatische Staudynamikanalyse: Automatic Tracking of Moving Jams*) are patent protected.

One should mention that Kerner rejects all traffic models containing a fundamental diagram and questions their applicability to modelling freeway traffic conditions. These are also the main reasons for controversies and criticism on the part of other traffic congestion researchers (Helbing & Schönhof, 2007).

2.1.2. Helbing's approach

Whilst Kerner along with Klenov, Konhäuser, Rehborn and many others propagated the idea of a three-phase traffic theory, another group of German physicists and traffic researchers, consisting of Helbing, Hennecke, Schönhof, Treiber, etc., disagreed with Kerner's arguments and expressed (to some extent) opposite opinions.

It is confirmed (Helbing & Schönhof, 2007) that none of the first-order models, such as the Lighthill-Witham-Richards (LWR) model, and none of the second-order traffic models is capable of reconstructing congested traffic states. As an alternative to these widely criticized (Daganzo, 1995) macroscopic models such as LWR and its extensions, Helbing et al. (1999) introduce a gas-kinetic-based traffic model (GKT model) that is expected to overcome the inconsistencies and inaccuracies of previous models.

Based on their simulations using that model as well as empirical research, they distinguish and define five different kinds of congested traffic states:

- Pinned localized clusters (PLC)
- Moving localized clusters (MLC)
- Stop-and-go waves (SGW)
- Oscillating congested traffic (OCT)
- Homogenous congested traffic (HCT)

Localized clusters cover short motorway sections and their length remains stable. PLC are fixed to certain locations, whereas MCL propagate upstream at characteristic speed. The congested states OCT and HCT stretch over longer motorway sections. The first is characterized by speeds frequently oscillating in the congested area, whereas in the latter the speeds are homogenously low (Helbing & Schönhof, 2007).

Unlike the classification by Kerner presented in section 2.1.1, which is founded on the analysis of single cross motorway cross-sections, Helbing's classification is based on spatiotemporal traffic dynamics. The states correspond with each other in the following way. Kerner's wide moving jam (J) might be compared to a moving localized cluster (MLC); a stationary and homogenous type of synchronized flow (S) would correspond to homogenous congested traffic (HCT); and a non-stationary and non-homogenous type of synchronized flow might relate to oscillating congested traffic (OCT).

2.1.3. BMW / Transver approach

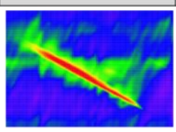
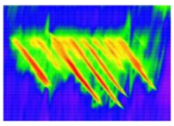
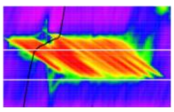
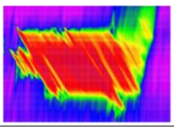
In 2010, the car manufacturer BMW commissioned the transport engineering consultancy Transver to prepare a report on congestion types and the relationship between traffic flow and the probability of a traffic breakdown based on the data from motorway sections from the Munich area: the A8, A9, A92, A94, A95, A96, A99 (TRANSVER GmbH, 2010).

The number of congestion types distinguished in this approach is limited to four:
- Short-term speed breakdown
- Stop-and-go wave
- Wide jam
- Mega jam

The reason for this new classification was to combine congestion with the impact it has on energy management in electric vehicles. Therefore, the classification algorithm operates using two jam characteristics: duration and number of stops. Knowledge about these properties allows effective short-term congestion forecasting, which is critical for efficient battery management in electric cars.

Due to an opportunity to cooperate with the consultancy Transver, we have decided to adhere to their methodology of differentiation between congested traffic states. It is unambiguous and transparent, and even more up-to-date now as the number of electric vehicles in the Austrian road network keeps growing. The approach has already been implemented in the analysis software from Transver, which is facilitative in processing large datasets.

A spatiotemporal graphic illustration of each of the above congestions states as well as descriptive criteria for the visual analysis are presented in Fig. 1.

Type of congestion	Spatiotemporal graphic example	Criteria for the visual analysis
Single congestion wave / short-term speed breakdown		A thin red stripe implying temporarily low velocity.
Stop-and-go wave		Several narrow red stripes representing congestion waves separated by green free-flow sections.
Wide jam		Broad area with predomination of "congestion colors" (red, orange, yellow).
Mega jam		Extensive area with the domination of "congestions colours" (red, orange, yellow) – a wide-spread traffic breakdown.

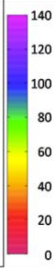


Fig. 1 Congestion types and corresponding definition criteria (TRANSVER GmbH, 2010)

Whether a traffic state is classified as a congestion or not depends on its measured velocity. A boundary value for a transition from free flow to a congested state has been established as 60 km/h (Kesting & Treiber, 2010). Further detailed classification of congestion types, depending on the duration of the congestion and the number of speed breakdowns, occurs according to the algorithm in Fig. 2.

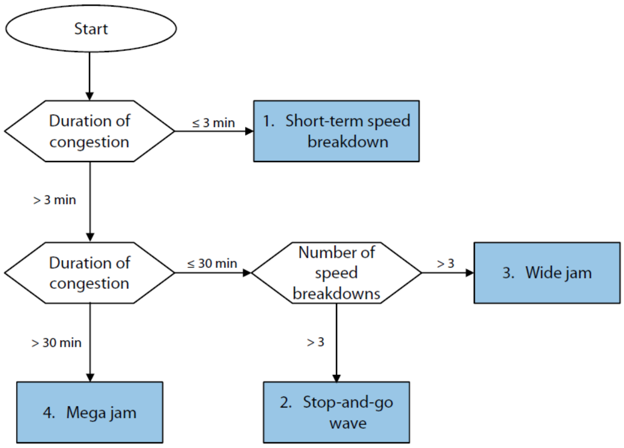


Fig. 2 Congestion classification algorithm

Once the detector data is processed and a general situation on the A12 and A13 motorways is analyzed and major patterns are recognized, one could apply other classification approaches. It is not inconceivable and, as discussed in section 3.3 of this paper, is well justified for the A13 with its non-standard features.

2.2. Adaptive smoothing method (ASM)

In principle, different methods and data sources can be used to detect and categorize traffic jams. Position data from vehicles (respective probe data or floating car data) allow detecting speed breakdowns as well as number and duration of stops very precisely but only for a limited number of vehicles. Roadside detectors (e.g. inductive loops) can only collect data from a specific cross-section but they detect all vehicles passing through. These data can be used to draw velocity contour plots. The traffic control system installed on the A12 includes roadside detectors with rather short interval operating permanently.

Since the detectors on the A12 are located at an average interval of 1.6-1.7 km, the resulting velocity contour plots would be of too low resolution, which might result in an incorrect interpretation of traffic congestion and the wrong classification of congestion types. Therefore, a crucial step in the study was to preprocess the raw loop detector data in a way that would eventually allow the creation of visually comprehensible and at the same time scientifically correct contour plots. This can be performed with the use of cumulative plots (Bertini, Lindgren, Helbing, & Schönhof, 2004) or by applying an adaptive smoothing method (ASM) (Helbing & Treiber, 2002). We chose the latter, as it was already integrated in the software CONSYST used in the study. In effect, it enabled us to mitigate the artifacts and discontinuities in the dataset and accurately reconstruct the traffic situation spatiotemporal phase diagrams of traffic flow. We could also investigate the propagation characteristics, differences and commonalities of disturbances on particular sections of the A12 and A13.

The Adaptive Smoothing Method (ASM) applies a non-linear spatiotemporal low-pass filter to the (incomplete) input data, filters out small-scale fluctuations and produces smooth velocity matrices. The method exploits some principal properties of traffic flow. That is, in free flow, perturbations propagate downstream (in the direction of traffic flow) with a typical velocity c_{free} of about 80% of the desired velocity, whereas, in the case of congestion, perturbations move upstream with a characteristic velocity c_{cong} close to -15 km/h (Helbing & Treiber, 2002). An illustrative comparison of two contour plots prepared with the use of the adaptive smoothing method and a simple isotropic interpolation is shown in Fig. 3 (Helbing & Treiber, 2002).

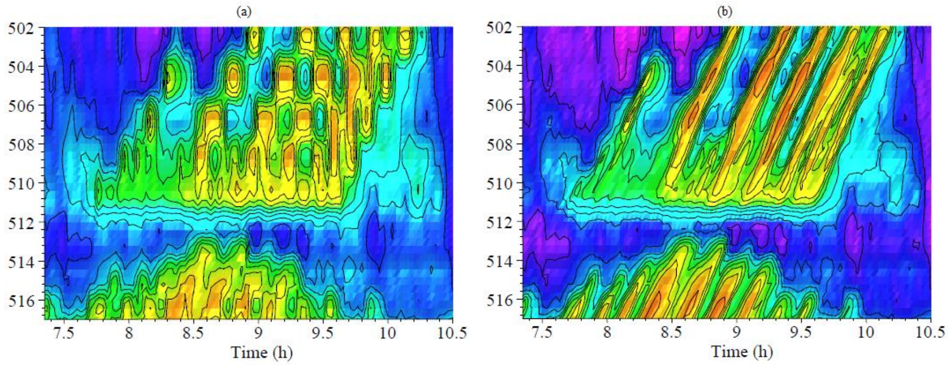


Fig. 3 Contour plots (inverted color gradation) created with the isotropic interpolation (a) and the adaptive smoothing method (b)

Default parameters for the ASM method are specified in Table 1 (Treiber & Helbing, 2003). According to (Kesting & Treiber, 2010), the velocity values do not need to be calibrated to a specific measurement site. However, the method is slightly more sensitive to the smoothing parameters σ and τ, which we describe in section 3.4. The ASM method provides reliable results as long as the distances between following detectors do not exceed 3 km.

Table 1. Default parameter values for the adaptive smoothing method (ASM)

Parameter	Typical value	Meaning
σ	0.6 km	Range of spatial smoothing in distance
τ	1.1 min	Range of temporal smoothing in time
c_{free}	80 km/h	Propagation velocity of perturbations in free traffic
c_{cong}	-15 km/h	Propagation velocity of perturbations in congested traffic
V_c	60 km/h	Transition threshold from free to congested traffic
ΔV	20 km/h	Width of the transition region

2.3. Measurement site and data processing

The analysis has been performed for the Tyrolean sections of the A12 and A13 motorways. Our study area extends over around 85 km of the A12 from Innsbruck (*Völs Kranebitten*) to Kufstein (*Kufstein Nord*). On the A13, it encompasses about 34 km between Innsbruck (*Innsbruck Süd*) and the Brenner Pass (*Brennersee*). These motorway segments frequently suffer from severe traffic problems and include several exceptional bottlenecks. Thus, they are particularly suitable for a congestion study.

Our analysis is based on traffic data from 53 detector stations on the A12 and 29 stations on the A13 motorway. The average distance between detectors is approximately 1.6 km and 1.2 km respectively. The data has been provided by the Austrian motorway administration ASFiNAG. **Błąd! Nie można odnaleźć źródła odwołania.** summarizes the characteristics of the A12, the A13 and additionally the A9 motorway in Germany, which we refer to later in the paper.

A meaningful issue is the use of specialized software, as it increases the efficiency and accuracy of processing large amounts of data. During the data processing stage, the data has been aggregated across all drive lanes and entered into the CONSYST software, which applies the adaptive smoothing method (ASM) to the raw detector data and produces space-time-velocity diagrams. In our study, we have chosen default parameters for the exponential filter τ = 1.2 min and σ = 0.6 km. Another feature of the software is the automatic detection of congestion incidents (Fig. 10 - black rectangles around the low-speed area) and calculation of corresponding time losses (difference between the real travel time and the free-flow travel time).

Table 2. Characteristics of the analyzed A12 and A13 motorways compared with the A9 in Germany

Feature	A12	A13	A9
Section	*Völs Kranebitten - Kufstein Nord*	*Innsbruck Süd - Brennersee*	*Munich-Schwabing - Holledau*
Length	85 km	34 km	47,6 km
No of lanes	2+2 (99%) / 3+3 (1%)	2+2 (47%) / 3+3 (53%)	3+3 (77%) / 4+4 (23%)
No of exits	17	7	13
No of detector stations	53	29	33
Speed limits	100 km/h (IG-L) (other limits according to dynamic traffic signs)	130/100 km/h (other limits according to dynamic traffic signs)	None (speed limits regulated by dynamic traffic signs)
AADT (in 2016)	48.164 (*Ampass*)	77.252 (*Gärberbach*)	146.579 (*Garching Nord*)
Others		Max. inclination 6,1%	Temporary release of hard shoulders for traffic

3. Results

3.1. Overview

An overall number of 2605 congestion incidents, out of which 2013 on the A13 and 592 on the A12, were detected in 2016. The highest amount of jams was recorded during the summer season, reaching almost 350 at its peak in July (Fig. 4).

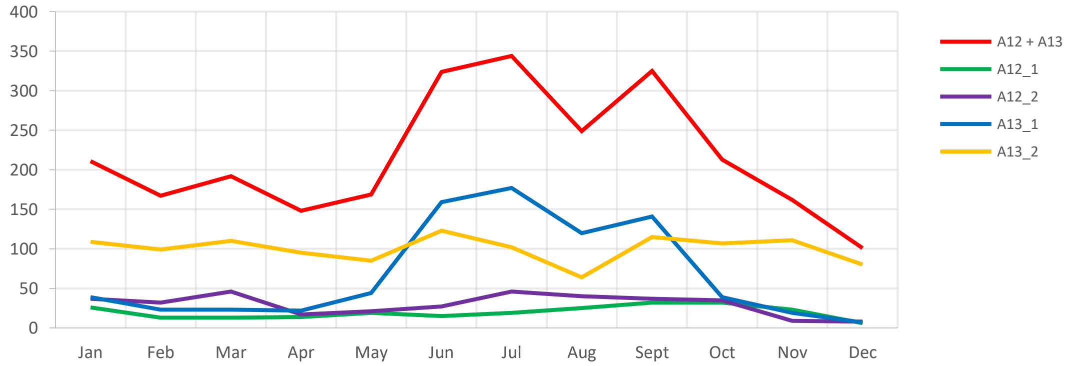


Fig. 4 Overview of the congestion incidents in 2016 on the A12 and A13 motorways
(A12_1 – Kufstein to Innsbruck, A12_2 - Innsbruck to Kufstein, A13_1 - Innsbruck to Brenner, A13_2 - Brenner to Kufstein)

Whilst the A12 proves relatively stable in terms of congestion throughout the year, the number of traffic issues on the A13 multiplies in the summer season, especially in the southbound direction. The areas notorious for congestion have been identified close to the motorway interchanges *Innsbruck-Ost*, *Innsbruck-Mitte*, *Innsbruck-West* and *Wiesing*.

The annual average daily traffic (AADT, Monday to Sunday) on one of the most frequented sections of the A12 between Innsbruck and Hall in Tirol reaches over 77.000 vehicles in both directions. The average HGV (Heavy Goods Vehicle) percentage has been estimated at 11%. On the A13 between interchanges *Zenzenhof* and *Igls-Patsch*, the AADT reaches 48.000 vehicles with almost 15% HGV share. If only the Saturdays are considered, the AADT on the A13 rises by 15% to 55.000 vehicles.

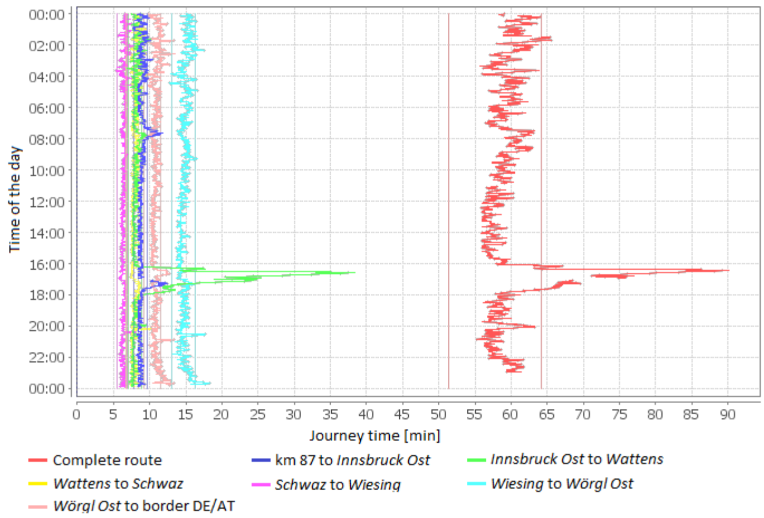


Fig. 5 Average journey times on 19th Jan 2016 on particular sections of the A12 in the direction to Kufstein

Each segment of the motorway has been treated separately in the study. An example of a journey time analysis on the A12 motorway, subdivided into sections spanning from one interchange to another, is illustrated in Fig. 5.

The identification of reasons for the congestion incidents was performed with the use of data from the ASFiNAG Traffic Information Centre (TIC). Preliminary results are showing 35% for vehicle breakdowns, 19% for congestion, 15% for accidents, 14% for road works and 17% for another reasons. However, we have experienced difficulties with the proper allocation of incident information and the correct interpretation of multiple messages. An alternative attempt is being made by applying publicly available Traffic Message Channel (TMC) data. Eventually, this should prove the relationship between congestion types and their causes. The effects of these endeavors are not available so far.

Thanks to the use of semiautomatic tools, the data processing has run relatively smoothly. Nevertheless, we have identified several obstacles in the classification process itself:

- Overlapping of bottlenecks and traffic incidents makes the classification much more complicated.
- The automatic differentiation between wide jams and stop-and-go waves does not always deliver the correct results. This has been overcome by producing plots with a very dense color scale and by manual recognition. A more efficient solution could be a simulation of vehicle trajectories based on Floating Car Data (FCD).
- Close attention must be paid to the smoothing parameters σ and τ controlling the adaptive algorithm.

3.2. Non-standard sections and time periods

Apart from the general difficulties in the classification process, pointed out in section 3.1, many other issues specific to our measurement site have been diagnosed.

Special consideration should be given to the A13, as its geometric and traffic parameters exceed the application range of our approach. Inasmuch as the inclination grade reaches up to 6.1% on some sections of the A13, very low velocities are common on the rightmost lane, occupied predominantly by HGVs and caravans. This forces the algorithm to incorrectly detect congestion even though it is still free flowing. This could be avoided by analyzing the lanes separately, which is scheduled as the next research task. Also, redefining the threshold values for congestion classification is being considered. In the next sections, we concentrate on the A12 only.

In fall 2015, owing to the political situation, Germany introduced temporary controls on its state border with Austria in Kufstein. This has significantly contributed to the increase in congestion on the A12 in the direction towards Germany. In further analyses, we have intentionally skipped 153 mega jams (between Innsbruck and Wiesing) that were triggered by state border controls, as they were not an effect of typical traffic-related factors.

3.3. Congestion patterns

A temporal distribution of congestion types on the A12 between Innsbruck and the state border (the whole length in both directions) is presented in Fig. 6. While the number of short-term speed breakdowns, stop-and-go waves and wide jams proves relatively stable throughout the year (except for February and December), mega jams culminate in summer months, which corresponds well with the increased tourist traffic during the vacation period. The overall number of congestion incidents reaches its peak in October.

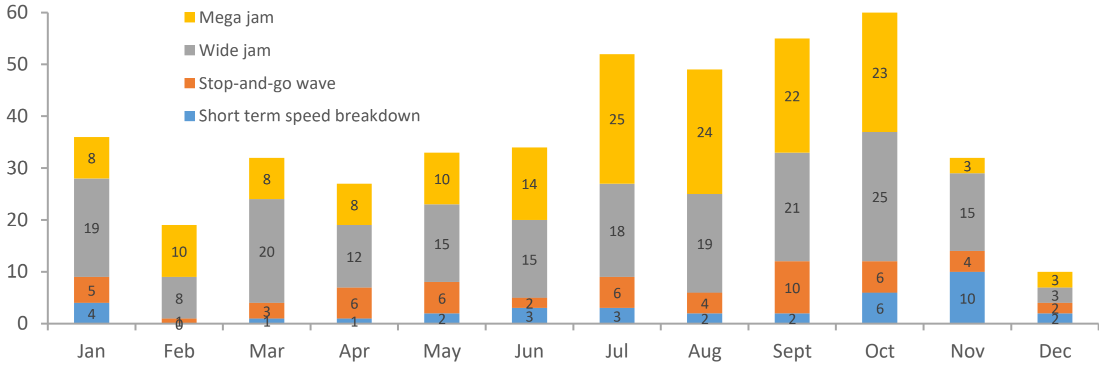


Fig. 6 Frequencies of congestion types on the A12 in both directions

However, the variation in congestion intensity during the week (Fig. 7a) and the day (Fig. 7b) implies that, despite seasonal tourist traffic increase, congestion is still shaped by local commute traffic, predominating in rush hours (7-8 AM and 4-6 PM) on workdays.

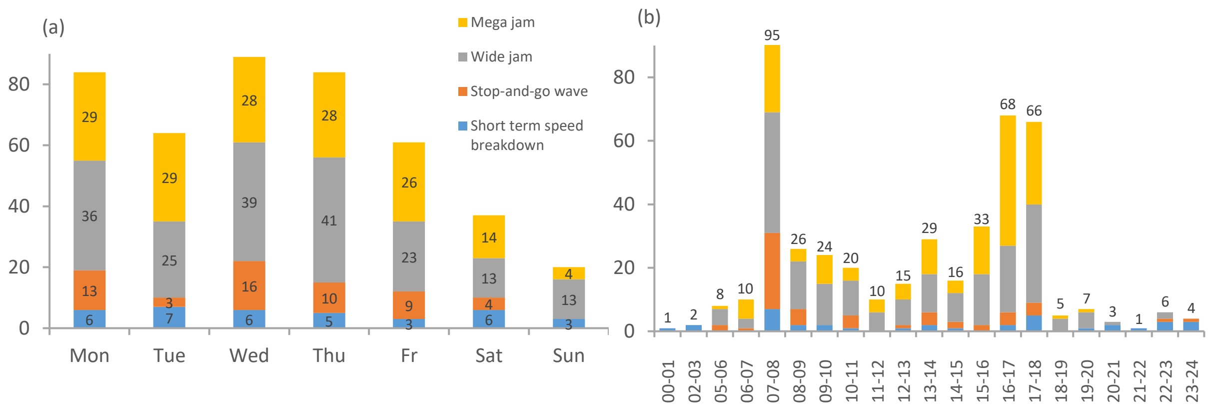


Fig. 7 Average frequencies of congestion types on the A12 broken down into days (a) and hours (b)

As far as the spatial distribution is concerned, the section between Innsbruck and Wattens proves most vulnerable to the occurrence of wide and mega jams (Fig. 8). This is not only due to the highest traffic volumes but also because of the concentration of bottlenecks in this area, i.e. successive on- and off-ramps, short weaving sections, tunnels and speed limits.

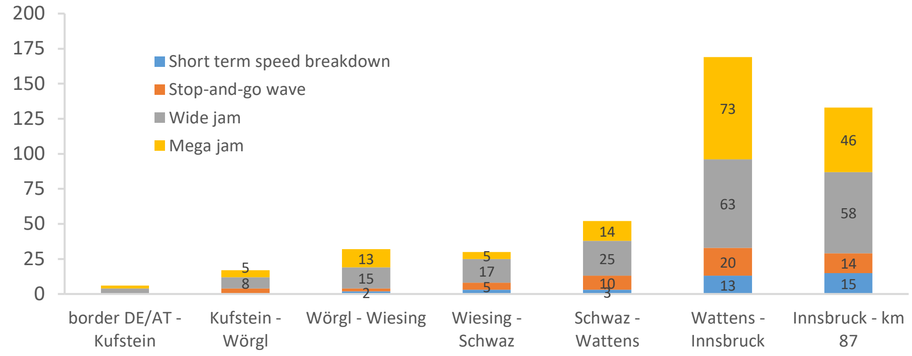


Fig. 8 Spatial distribution of congestion types on different sections of the A12

Thanks to a comparison with the results of a similar study carried out by Transver (2010) for the A9 motorway between motorway junctions *Munich-Schwabing* and *Holledau* in Germany, we get another valuable insight into the traffic situation on the A12 (Fig. 9). One can easily perceive the prevalence of severe traffic states on the A12, i.e. mega jams and wide jams, compared to the A9 where short-term speed breakdowns dominate. It also indicates how prone the Austrian A12 is to congestion issues, many of which inevitably develop from minor disturbances to wide and mega jams, according to velocity contour plots.

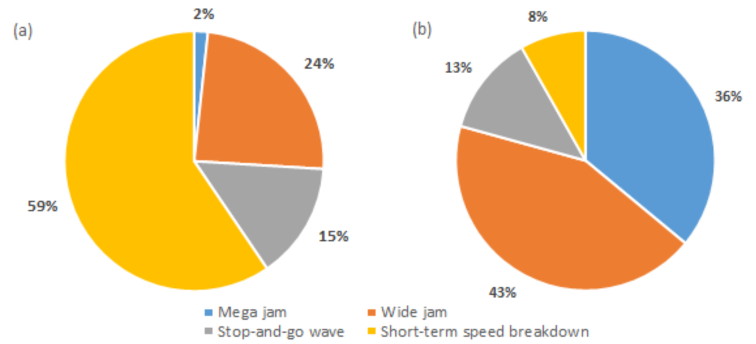


Fig. 9 Percentage shares of congestion types on the A9 in Germany (a) and A12 in Austria (b)

3.4. Sensitivity of the ASM method and influence of parameters on the results

As has been mentioned in previous sections, the σ parameter might have a decisive impact on the number of detected congestion incidents. The parameter controls the strength of the filter that smooths all high-frequency spatial fluctuations on a length scale smaller than σ (Helbing & Treiber, 2002). That is, too small values can lead to a locally limited smoothing and cause coarse gradation and uneven steps in the contour plots. In effect, there could be too many incidents found, which we have come across when analyzing the data from the A13. In specific cases (lower velocities, numerous successive disturbances), choosing a higher σ value is recommended. We are currently experimenting with different σ values for the A13. A comparison of velocity contour plots for σ = 0.6 km and σ = 2.0 km is presented in Fig. 10. Black rectangles indicate automatically recognized congested states.

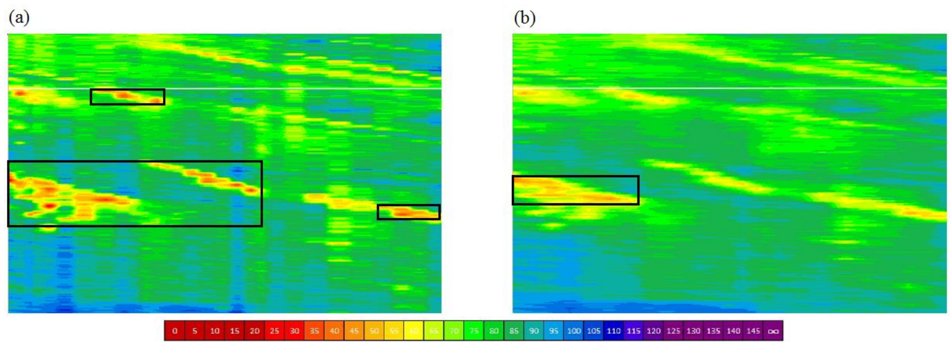


Fig. 10 Velocity contour plots calculated using the smoothing parameter σ = 0.6 km (a) and σ = 2.0 km (b)

4. Conclusions

This paper gives an overview of the traffic situation on the A12 and A13 motorways and provides a detailed insight into congestion patterns on the A12 between Innsbruck and the state border. Our analysis contributes significantly to the understanding of traffic congestion patterns on motorways located in specific alpine regions. It is the first time that assumptions and hypotheses about traffic jams in the Tyrol have undergone a thorough scientific assessment and have been verified by numbers. It also provides a sound basis for the development of ITS strategies with specific measures (e.g. information, guidance, control) addressing different congestion types and related traffic patterns as well as incidents and their consequences. A separate study should be performed to define the most effective strategies, choose the appropriate technical solutions for the bottlenecks identified in current study and simulate the effects for different scenarios and time horizons.

As we argue in section 3.3, the weekly and daily distribution of congestion resembles a typical local commute traffic load. However, a broader look at the temporal congestion frequencies throughout the whole of 2016 and a comparison with a similar study performed for the A9 in Germany prove that the Austrian A12 experiences exceptionally more severe traffic disturbances than the A9. But it is not only local traffic which is to be blamed. Daily commuters overlapping with substantial truck transport as well as seasonal waves of tourists coming in from neighboring countries are responsible for this state. Apart from that, the geographical location of the A12 and the topography of the Tyrol do not allow for easy rerouting. In addition, the number and location of bottlenecks, particularly between Innsbruck and Wattens, increase exposure to potential congestion incidents.

The A13 motorway, due to its geographical location, geometric design, harsh weather conditions and its crucial role in the transport corridor through the Alps, as well as due to the influence of the toll station *Schönberg im Stubaital*, appears to be a one-of-its-kind case and requires further specialized analyses and redefinition of the parameter values for smoothing and classifying algorithms.

Nevertheless, further analyses are required to describe conditions on the A12 and A13 in detail. The research potentials are in particular: reconsidering the congestion on nearside and offside lanes separately, optimization of parameter values in the classification algorithm and the adaptive smoothing method, and validation of macroscopic results with microscopic Floating-Car-Data (FCD). Eventually, the outcomes will facilitate reflection on the ITS (e.g. installation and use of information boards, signing, traffic control systems) and policy measures or investments to be undertaken at specific points on the A12 and A13 motorways to ease the congestion, decrease time losses and, as a result, reduce the financial and social costs of traffic.

Acknowledgments

The authors would like to thank ASFiNAG and its employees for providing the necessary traffic data, Prof. Bernhard Friedrich from the consultancy TRANSVER as well as Stefan Gürtler for his assistance, valuable remarks and the effort he has put into data processing.

5. References

Bertini, R. L., Lindgren, R. V., Helbing, D., & Schönhof, M. (2004). Empirical analysis of flow features on a German autobahn. *Proceedings of the 83rd Annual Meeting of the Transportation Research Board.* Washington, D.C.

Bogenberger, K., & Huber, G. (2013). Verkehr besser verstehen und Verkehrsprobleme optimal lösen. *Politische Studien 452*, pp. 20-29.

Daganzo, C. F. (1995). Requiem for second-order fluid approximations of traffic flow. *Transportation Research. Part B, 29*, pp. 277-286.

Helbing, D., & Schönhof, M. (2007). Empirical Features of Congested Traffic States and Their Implications for Traffic Modelling. *Transportation Science, 41(2)*, pp. 135-166.

Helbing, D., & Treiber, M. (2002). Reconstructing the Spatio-Temporal Traffic Dynamics from Stationary Detector Data. *Cooperative Transportation Dynamics, 1*, pp. 3.1-3.24.

Kerner, B. S. (2004). *The Physics of Traffic.* Berlin-Heidelberg: Springer.

Kerner, B. S. (2009). *Introduction to Modern Traffic Flow and Control. The Long Road to Three-Phase Traffic Theory.* Berlin-Heidelberg: Springer.

Kerner, B. S., & Rehborn, H. (1996). `Experimental Properties of Complexity in Traffic Flow. *Physical Review E, 53*, pp. R4275-R4278.

Kerner, B. S., Rehborn, H., Aleksic, M., & Haug, A. (2004). Recognition and tracking of spatial–temporal congested traffic patterns on freeways. *Transportation Research Part C 12*, pp. 369-400.

Kesting, A., & Treiber, M. (2010). *Verkehrsdynamik und -simulation.* Berlin-Heidelberg: Springer.

TRANSVER GmbH. (2010). *Stauklassifizierung und Untersuchung des Zusammenhangs Verkehrsstärke und Verkehrszusammenbruch.* Munich.

Treiber, M., & Helbing, D. (2003). An Adaptive Smoothing Method for Traffic State Identification from Incomplete Information. In H. Emmerich, B. Nestler, & M. Schreckenberg, *Interface and Transport Dynamics. Computational Modelling* (pp. 343-360). Springer.

Treiber, M., Hennecke, A., & Helbing, D. (1999). Derivation, properties and simulation of a gas-kinetic-based, non-local traffic model. *Physical Review E, 59*, pp. 239-253.