Intersection with Highly Adaptive Traffic Lights Can Still Be Suitable for C-ITS Service GLOSA

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Abstract: The C-ITS service “Green Light Optimal Speed Advisory” (GLOSA) is a highly promising Day1.0 services for efficient, environmentally friendly and safe cooperative transport. It will play a crucial role in the increasing automation of assistance and driving functions in cooperative connected automated mobility (CCAM). Over the past three decades, significant efforts have been made to make traffic light signalling as adaptable as possible to traffic requests. However, there is a common belief that the more flexible the control, the less reliable the forecast and thus the functionality of GLOSA. This paper introduces stability indicators to demonstrate that this belief is only partially accurate. The proposed tool allows for the analysis of historical data from existing systems to derive an indicator for the quality and suitability of the C-ITS GLOSA application. We demonstrate the feasibility of the approach using real world data from the C-ITS corridor Hamburg, Germany.

1 OBJECTIVES AN MOTIVATION

Safety and environmental compatibility within the mobility sector are the main objectives of the coming years and an essential building block for ensuring an efficient mobility transition. With increasing automation and cooperation between the infrastructure and the vehicles via so-called Car2X communication, the prerequisites for this are being created. The need for C-ITS services will increase as they can be directly integrated into driving functions of automated and autonomous vehicles. All services of cooperative intelligent transport systems (C-ITS) serve to improve traffic safety, increase the efficiency of the traffic network or ensure environmentally friendly transport. On the one hand, these C-ITS applications can be warning services (e.g., traffic jam warning, road works warning, accident warning) but also information services (e.g., traffic light phase assistant, route recommendations, speed limits).

Traffic lights are and remain the bottlenecks of urban traffic. Increasing automation and digitalization will not change that. Where large traffic volumes collide, the only option, also in the future, will be to separate them temporally. This need will remain as long as not all road users are connected and automated. Since we always take pedestrians and cyclists into account in urban areas - which also contributes to the climate aims - there will be not more intersections without traffic lights in the foreseeable future. This makes it even more necessary to efficiently utilize the previously unused potential of signalized intersections. To this aim, cooperative systems offer a range of services that can be used accordingly. One of the most frequently discussed services at the moment is the C-ITS service GLOSA. This is often simply referred to as the traffic light phase assistant. In addition to transmitting the signal status information, the GLOSA service also transmits information about the remaining red and green times. The forecast algorithm and its accuracy have already been examined in several research papers, for example, as statistical prediction model for traffic lights via Kalman filtering (Protschky et al., 2014), via support vector machines (Weisheit et al., 2014), via machine learning algorithm (Scheegans et al., 2022) or via Markov chain (Otto et al., 2013; Barthauer et al., 20214). Confidence intervals regarding switching time difference in consideration of the lead time to the signal change were first

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discussed in (Bodenheimer et al., 2015). The GLOSA service also transmit speed recommendations for the optimal approach to the intersection via the SPATEM/MAPEM C-ITS message.

Coordinated roads and thus the use of GLOSA is subject to certain boundary conditions, which are described in (Otto et. al., 2010; Genser, 2022). This is the problem that is currently often discussed in research papers. The hypothesis here is often that the more flexible the control, the less reliable the forecast and thus the functionality of GLOSA. The efforts of the last 30 years to implement the most flexible control possible, which adaptively takes into account the needs of all road users, seem to be in extreme contradiction to the requirement for a stable forecast for the GLOSA service. Due to certain boundary conditions in the transport network, there are conditions that are ideal for the quality of the forecast. These are, for example, coordination. This is exactly where this hypothesis can be refuted. Research on this was already carried out (Eckhoff et al., 2013; Eteifa et al., 2021; Krumnow, 2023; Mellegård et al., 2020; Suzuki et al., 2020).

Increasing digitalization is clearly accompanied by increasing availability of data. This not only happens spatially, but the requirements for temporal access - such as real-time capability – also underwent a complete change. Current requirements are not comparable to the requirements on conventional traffic management systems and applications. Until recently, it was not necessary for traffic monitoring and control to meet real-time requirements. However, due to increasing digitalization, the necessities of connected and automated driving, security requirements, and new services in the C-ITS area, cities and municipalities are facing completely new challenges. This is one of the reasons for the current focus is on transport infrastructure. There is an enormous amount of catching up to do in terms of open data provision while at the same time implementing security mechanisms for the critical infrastructure as well as dedicated user and rights management.

Virtual traffic lighting is also often discussed in the literature (Bazzi et al., 2016; Zhang et al., 2018). In this case, physical signals could be completely dispensed with. However, since a physical signal will always be necessary for VRUs such as cyclists and pedestrians, this approach will not be considered further here.

For the reasons mentioned, so-called open data access to data from the operational transport infrastructure has so far been rare. The city of Hamburg is one of the pioneers in Germany in this regard. Real-time data from a variety of traffic lights in Hamburg can be accessed via Hamburg's urban data platform or the Mobilithek as national access point for ITS data in Germany. The data set contains process data for a large number of intersections in Hamburg. Among other things, current signal state information can be accessed in real-time. There is also data from detector inputs from pedestrians, cyclists, vehicles, and public transport. An example of this is shown in Figure. 1.

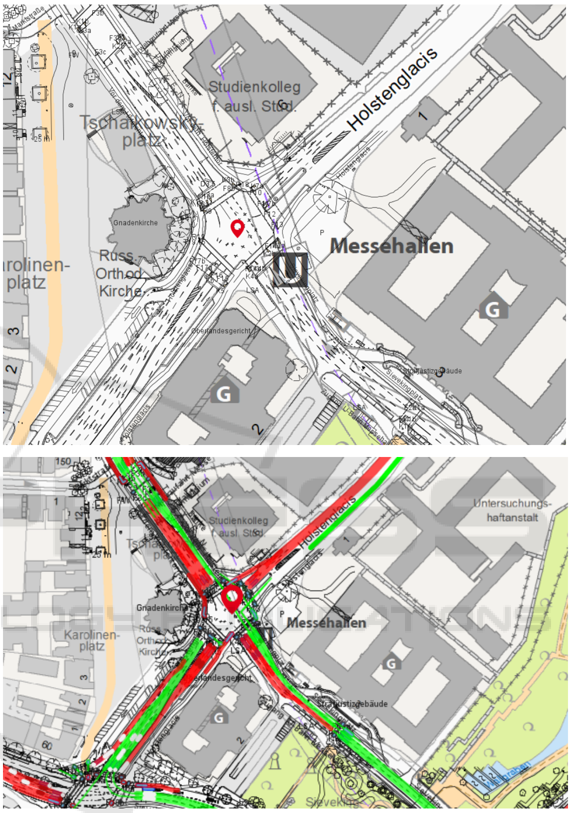

Figure 1: Open data example – no.537 [geoportal-hamburg.de] upper: geometry of the intersection including signal layout plan lower: current signal status of the LSA including MAPEM and SPATEM information.

This paper introduces stability indicators based on the publicly available traffic data. Here we build on previous work (Otto et al., 2022), where we introduced the theoretical background for the analysis of signalized intersections. Furthermore, (Jeschor et al., 2024) show results of a large-scale predictability evaluation in Hamburg, which also provide statements about consistency.

The derived tool enables the analysis of historical data from existing systems to derive an indicator for the quality and suitability of the C-ITS GLOSA application. We can show that intersections with highly adaptive traffic control schemes can still be suitable for GLOSA.

2 METHOD

Basis of our analysis is the data set provided by the city of Hamburg. Our goal was to derive stability indicators for a wide range of intersection topologies and traffic volumes. For this reason, the characteristics of the intersections in question should be completely different. In the end, we settled on three different intersections (277, 353, 835). The structural design of these intersections can be seen in the aerial photos in Figure 2.

Figure 2: Intersections no.277, no.353 and no.835 (up to down) [maps.google.com] intersection with different structural characteristics as well as different traffic volumes and relations.

The chosen intersections can be described as follows:

- Intersection no.277: This is the largest intersection in the selected subset. Traffic volumes are high during peak hours and signalization is relatively complex. The systems are designed with traffic-adaptive control. The signal programs are designed in such a way that they can react to traffic fluctuations during the day. Cycling and pedestrian traffic are carried on almost all routes.
- Intersection no.353: This is a relatively typical intersection with a medium geographical extent. The traffic load also differs throughout the day, to which the implemented adaptive control can react.
- Intersection no.835: Within the specified selection, this is a T-intersection that has the lowest complexity.

Our analysis is based on the signaling parameters of the intersections. Our research hypothesis is that these alone are sufficient to find stability indicators, regardless of intersection layout and size. The following parameters were examined:

- Number of signal programs and activated times of these programs,
- Cycle time of signal programs throughout the day,
- Length of the green time and area of the green time based on the cycle second,
- Sequences of green times in cycle and variation of the sequences,
- Variation of green start and green end of the signal groups in the cycle based on the signal program,
- Relation via matrices of the start times and end times of the signal groups to each other to analyze the interval,
- Representation of the probabilities of the signal groups for green in the cycle based on the data.

Based on the parameters mentioned above, it should be determined which of these factors can be used significantly to map the GLOSA suitability of adaptive controls.

3 RESULTS

The results are evaluated based on the three intersections described above. To simplify the presentation, only the results of intersection 353 are presented and shown specific in this paper. This is intended to facilitate general understanding and provide an easy introduction to the scientific evaluations of the tool.

3.1 Geo Data

The geographical coordinates of the individual signal groups at the intersection were extracted from the data and clearly displayed using the GIS program QGIS and the Google satellite map. Fig. 3 shows intersection 353 with all primary signal groups. The signal groups are separated by color according to lane type.

Figure 3: Visualization of geo data at intersection 353 – no of intersection as well as no of signal controller [maps.google.com].

In addition to vehicle and pedestrian signal groups, there are also signal groups for bicycle and bus lanes with the corresponding signaling systems at this intersection. Mixed lane types are also available. In total, there are 36 signal groups.

3.2 Length of Green and Cycle Time

First, the duration of the green state for each signal group at the intersection was determined from the data. For this purpose, the observation times for vehicle, bus and bicycle signal groups were extracted from the existing data. The selected data were sorted according to its time in order to determine the time difference in seconds between successive green and amber, green and red or green and dark. The following Figure 4 upper part shows an example of the green phase duration for the vehicle signal group 353_10. The times were grouped on the x-axis by the hours of the day and presented with boxplots. It can be seen from the figure that the green times show a large variance with the exception of 00:00 to 03:00, 17:00 to 19:00 and 22:00 to 23:00.

A similar procedure was used to determine the cycle times. For this purpose, only times with signal state green were extracted from the data. Regardless of the lane type, the cycle time was then determined from the sorted data using the time differences between two consecutive green. The following Fig 4 lower part shows the cycle time using the example of the vehicle signal group 353_10. Similar to the green stages, the cycle times also show variances, with the exception of the times from 00:00 to 03:00, 17:00 to 19:00 and 22:00 to 23:00. Furthermore, it becomes clear that the average from 00:00 to 04:00 and 20:00 to 22:00 is 75 seconds, while at the other times with the exception of the three hours from 09:00 to 10:00 a.m. as well as 1:00 p.m. to 2:00 p.m. and 11:00 p.m. to midnight is 90 seconds. (see Figure 4 lower part)

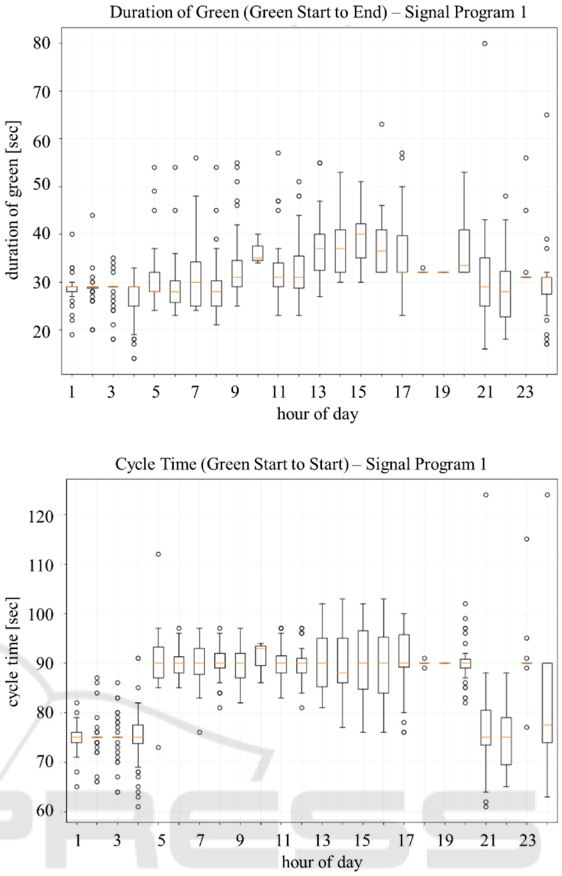

Figure 4: Intersection no.353 – upper: duration of green phases for signal program 1 and signal group 353_10 throughout the day lower: duration of cycle time for signal program 1 and signal group 353_10 throughout the day.

3.3 Signal Programs

In the next step, the signal program data was evaluated separately for each signal group.

For this purpose, all observation times were recorded from the data using the respective signal program and sorted by time. The observation time indicates the time of switching to another program. In the following Figure 5, the data for a period of three days from February 1st, 2023 (Wednesday) to February 3rd, 2023 (Friday) was presented.

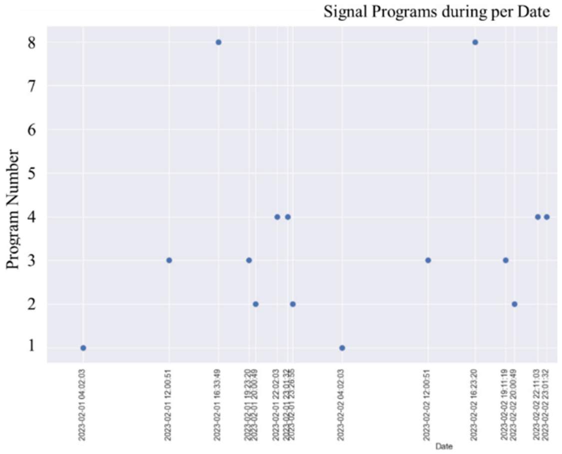

Figure 5: Intersection no.353 – current no of signal programs throughout the day.

3.4 Sequences

In the first step of the evaluation, the sequence was determined. This indicates the order in which the signal groups switch to green, taking into account the current signal program. For this purpose, only the observation times in which the signal color was green were extracted from the data. These dates were sorted by their time. The entire day's data was then assigned to the current signal program according to its time. The first signal group in the series is the one with the lowest time in the signal program data group. This signal group is fixed at position 1. The sequences are then recorded according to their time. A new sequence starts with the next recurrence of the fixed signal group. The following figures show examples of the signal group sequences for two signal programs.

The frequency of the sequences was made visually visible using transparent dots. Sequences shown in very pale blue occur only rarely, while the main strands are marked in strong blue. The representations show significant differences in the variance of the sequences. While the signal programs 1 have a large number of sequences and sometimes have several main sequences, a clearly fixed sequence can be seen in the signal programs 4.

3.5 Start and end Times of Green Signal

To evaluate the specific green start and green end times within the signal group sequence, the observation times were extracted from the data, which contained the signal colors green to amber for the vehicle signal groups or green to red for the pedestrian signal groups. The data was assigned to the current signal program according to its time. Analogous to the procedure for determining the signal group sequence, the first signal group to appear was fixed and the sequences were then determined based on the data with the signal color green. The following figures show the results for the signal programs.

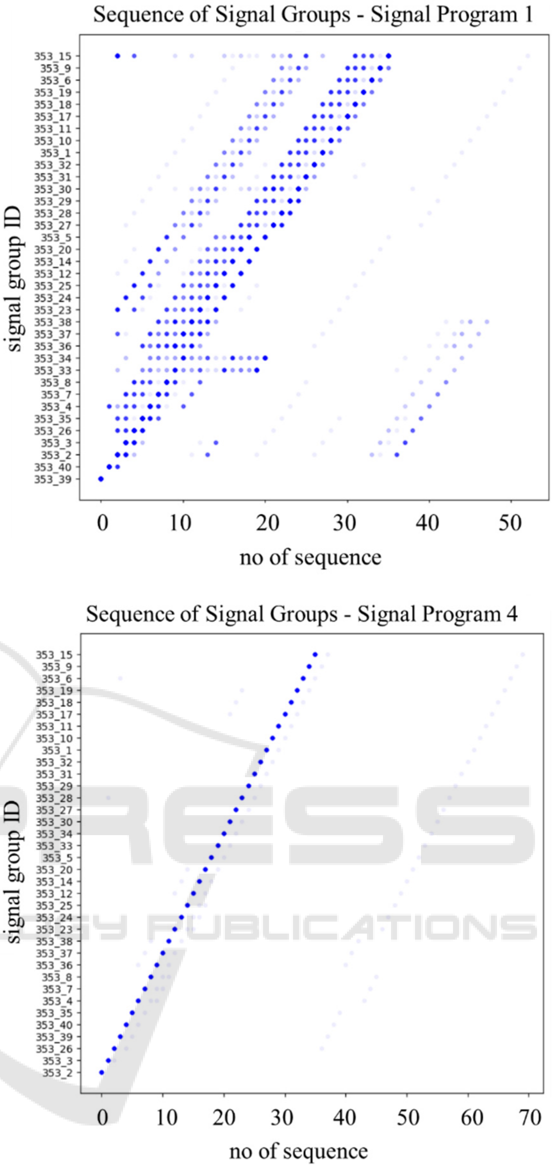

Figure 6: Intersection no.353 – sequence of signal groups - upper: program 1 – lower: program 4.

The time difference in seconds to the fixed signal group at position 1 is plotted on the x-axis. The transparency of the points indicates the frequency of occurrence of the green start (shown in green) and green end times (shown in orange). As with the determination of the sequences, it is also clearly visible from these figures that signal programs 1 has a clear variance in the green start and green end times, while signal programs 4 largely has fixed time differences as well as fixed green start and green end times.

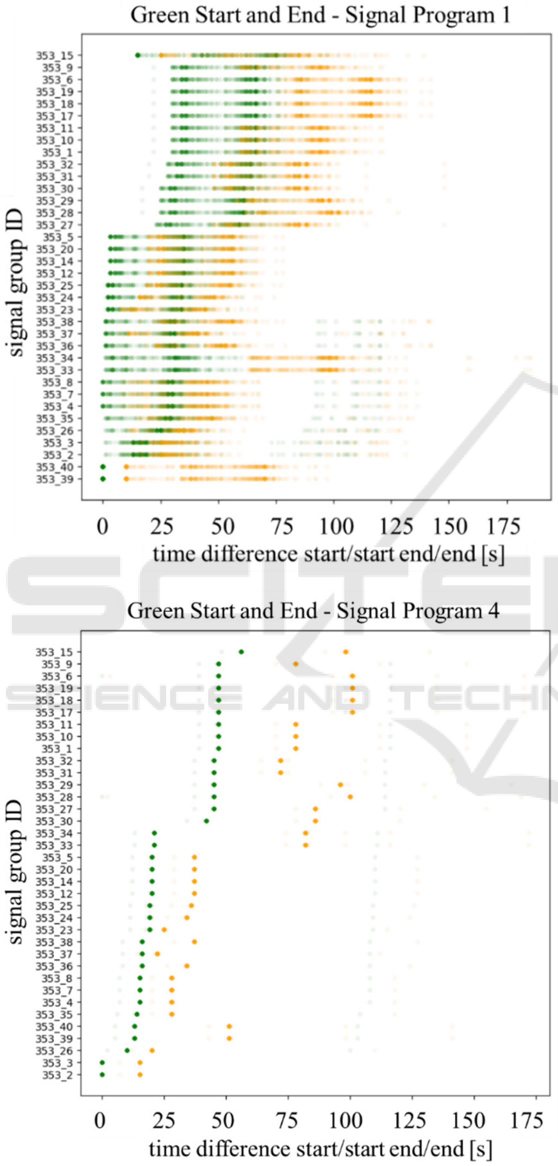

Figure 7: Intersection no.353 – start/end green upper: program 1 – lower: program 4.

3.6 Matrix Interval Between Signal Groups

An essential factor for the evaluation is the time intervals between the signal groups. Before the matrices could be set up, the specific times between the green starts (GA) and ends (GE) in all four combinations (GAGA, GEGA, GAGE, GEGE) as well as their variance had to be determined. The following figure shows an example of the result of the GAGA time differences for the vehicle signal group 353_10 in signal program 2. All signal groups are plotted on the x-axis.

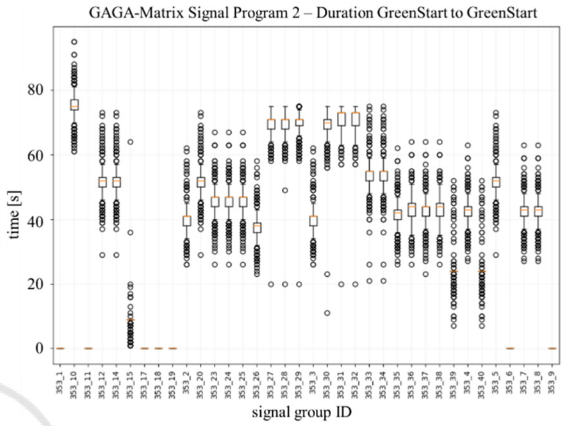

Figure 8: GAGA-matrix signal program 2 – example of duration between greenstart and next greenstart.

In this case (GAGA time difference), the cycle time is shown for the signal group 353_10 to itself. It can be seen that without exception the signal group 353_10 switches to green at the same time as the signal groups 353_1, 353_11, 353_17, 353_18, 353_19, 353_6 and 353_9, since the time difference here is 0 in each case. Fixed time differences can also be seen for the signal groups 353_15, 353_39 and 353_49, although there are some outliers. This gives a clear indication of the interval in the stage transition. For all other signal groups, time differences with significant variances can be seen. The box plots were drawn up for each individual signal group and for all four combinations (GAGA, GEGA, GAGE, GEGE). They form the data basis for the matrices.

The intervals of the box plots from the bottom to the top whiskers were first determined in the matrices. To assess and visualize the forecast of the green starts and ends of a signal group relative to the times of the other signal groups. The intervals were classified into the groups 0 to 3 seconds (green, well predictable), > 3 to 7 seconds (yellow, moderately predictable) and > 7 seconds (red, poorly predictable). The intervals and their respective classification in this color scale are shown in the matrices. Example matrices can be seen in the following figures.

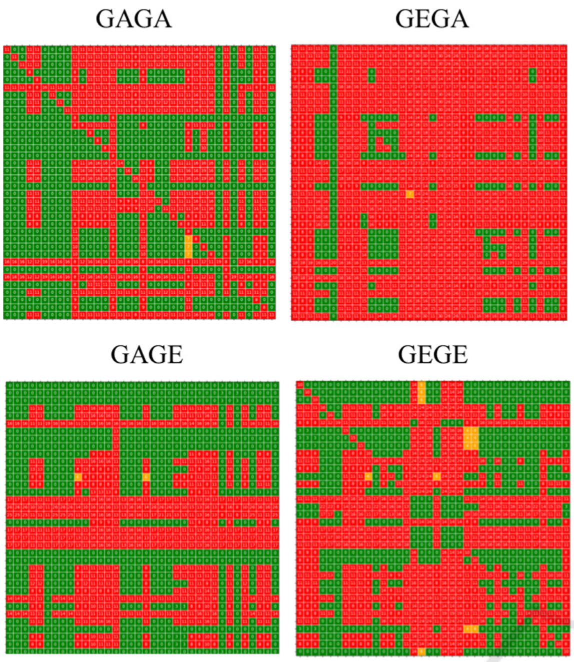

Figure 9: Example matrices of GAGA, GEGA, GAGE and GEGE – signal program 2.

After setting up the four individual matrices, all matrices were overlayed. For this purpose, the individual cell values of the four matrices were compared with each other. The smallest cell value from the four matrices is given in the overlay matrix. The following figure shows the overlay matrix for signal program 2.

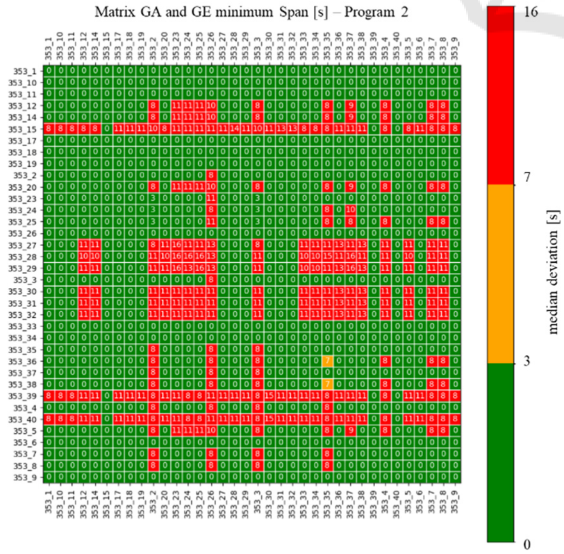

Figure 10: Example matrix green start to green end minimum span visualization.

The representation shows which signal groups can be predicted well or poorly with regard to the light signal changes of another signal group.

3.7 Probability of Green per Cycle

As a final step in the evaluation, the green times per cycle time were evaluated. For this purpose, the main strands of the signal group sequence as well as the green start and green end times were used as a basis. The green times resulting from the time difference between the start of green and the end of green were used to determine the frequency with which the signal group is switched to green and at what second of switching. The following figure shows an overview of the green phases for signal program 1.

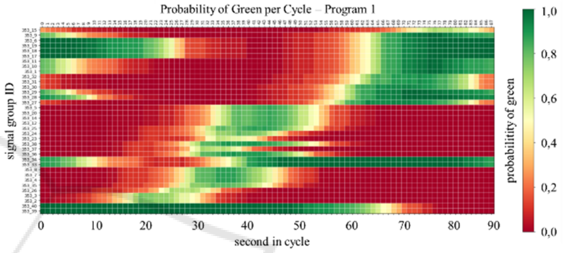

Figure 11: Intersection no.353 – Probability of green per cycle- program 1.

The most frequently occurring sequence plus all sequences with at least 80% similarity of the respective sequence to the main sequence was used as the data basis. The intensity of the green or red cells visualizes the probability with which the signal group shows the red or green status at the respective cycle seconds.

Although the intersections in question show a certain variability in signal programs, cycle time, etc. our analysis has shown that due to interrelation between the different signals there follows a certain predictability of the signal program. This becomes apparent in Fig. 10, where most cells in the predictability matrix are zero, i.e., there is at least one relation (green start/end, red start/end) between the signals based on a fixed time period. This allows a high-quality forecast based on current signal states or more specifically signal state changes. In addition to this short-term information, historical analysis also yielded certain signal groups and time periods within the cycle, where a certain status of the signal can be assured (comp. Fig. 11).

4 CONCLUSIONS

The commonly suggested thesis in research work and in traffic engineering practice that the more flexible the control, the less reliable the forecast and thus the functionality of GLOSA could be refuted in this research. The efforts of the last 30 years to implement the most flexible control possible, which adaptively takes into account the needs of all road users, apparently contradict the requirement for a stable forecast for the GLOSA service. In this article, a tool chain was presented that shows indicators that at least partially refute this thesis. The tool enables the analysis of historical data from existing systems to derive an indicator of the quality and suitability of the C-ITS GLOSA application.

Based on the presented and differentiated systems, it is clear that there are defined indicators that can provide information about the stability of the forecast both in the planning process and in the operation of the system. The prediction is then easily possible for most signal groups despite adaptive control over the intermediate times. This leads to very good results within the overall forecast, especially when superimposing a long-term forecast from historical data with a short-term forecast using sequence, cycle time, green time and intermediate time matrices.

It should be said here that the toolchain mentioned is evaluated by traffic lights of only one city. The systems correspond to the typical planning principles in Germany and Europe. In most cases, rule-based logic is stored, which has a fixed circulation time. Furthermore, the traffic light programs are phase-related controlled, where fixed phase transitions, minimum and maximum release times and other boundary conditions such as coordination - so-called green waves - exist. Obviously, these boundary conditions do not apply worldwide, but they are easily applicable throughout Europe.

Finally, it should be noted that the detector inputs are of course also of crucial importance, especially for short-term forecasts. This influence has currently only been taken into account indirectly. The aim of further investigations will be to determine correlations between the detector inputs and the corresponding signal groups. The prioritization in particular, the registration for the prioritization of public transport, is often done very early and can therefore be easily taken into account in the forecast. This influence will be taken into account in further analysis and research.

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REFERENCES

Barthauer, M., & Friedrich, B. (2014). *Evaluation of a signal state prediction algorithm for car to infrastructure applications.* Transportation Research Procedia, 3, 982-991.

Bazzi, A., Zanella, A., & Masini, B. M. (2016). *A distributed virtual traffic light algorithm exploiting short range V2V communications*. Ad Hoc Networks, 49, 42-57.

Bodenheimer, R., Eckhoff, D., & German, R. (2015, October). *GLOSA for adaptive traffic lights: Methods and evaluation.* In 2015 7th International Workshop on Reliable Networks Design and Modeling (RNDM) (pp. 320-328). IEEE.

Eckhoff, David, Bastian Halmos, and Reinhard German (2013). *Potentials and limitations of green light optimal speed advisory systems.* IEEE Vehicular Networking Conference. IEEE, 2013.

Eteifa, S., Rakha, H. A., Eldardiry, H. M., & Center, E. (2021). *Estimating Switching Times of Actuated Coordinated Traffic Signals: A Deep Learning Approach* (No. UMEC-039). Urban Mobility & Equity Center.

Genser, A. (2022). *Machine learning for traffic management in urban transportation networks* (Doctoral dissertation, ETH Zurich).

Jeschor, D., Matthes, P., Springer, T., Pape, S., & Fröhlich, S. (2024, June). *Cloudy with a Chance of Green: Measuring the Predictability of 18,009 Traffic Lights in Hamburg.* In 2024 IEEE Intelligent Vehicles Symposium (IV) (pp. 2882-2889). IEEE.

Krumnow, M. (2023). *Prädiktion von Signallaufzeiten verkehrsadaptiver Lichtsignalanlagen zur Unterstützung von C-ITS Anwendungen.*

Mellegård, N., & Reichenberg, F. (2020). *The day 1 C-ITS application green light optimal speed advisory—A mapping study.* Transportation Research Procedia, 49, 170-182.

Otto, T., & Hoyer, R. (2010). *Operating conditions of on-board displayed green wave speeds via V2I-communication.* Proceedings fovus-Network for Mobility.

Otto, T., Klöppel-Gersdorf, M., & Partzsch, I. (2022, August). *A Framework for Urban C-ITS GLOSA Evaluation.* In Conference on Sustainable Urban

Mobility (pp. 382-392). Cham: Springer Nature Switzerland.

Otto, T., & Weichenmeier, F. (2013). *Self-learning algorithm and signal state prognosis at traffic lights for V2I applications.* In Proceedings 20th ITS World Congress ITS Japan.

Protschky, V., Wiesner, K., & Feit, S. (2014, June). *Adaptive traffic light prediction via Kalman filtering*. In 2014 IEEE Intelligent Vehicles Symposium Proceedings (pp. 151-157). IEEE.

Scheegans, L. E., Heckmann, K., & Hoyer, R. (2022, September). *Exploiting Stage Information for Prediction of Switching Times of Traffic Actuated Signals Using Machine Learning*. In 2022 12th International Conference on Advanced Computer Information Technologies (ACIT) (pp. 544-548). IEEE.

Suzuki, H., & Marumo, Y. (2020). *Safety evaluation of green light optimal speed advisory (GLOSA) system in real-world signalized intersection.* Journal of Robotics and Mechatronics, 32(3), 598-604.

Weisheit, T., & Hoyer, R. (2014). *Prediction of switching times of traffic actuated signal controls using support vector machines*. In Advanced Microsystems for Automotive Applications 2014: Smart Systems for Safe, Clean and Automated Vehicles (pp. 121-129). Springer International Publishing.

Zhang, R., Schmutz, F., Gerard, K., Pomini, A., Basseto, L., Hassen, S. B., ... & Tonguz, O. (2018, August). *Virtual traffic lights: System design and implementation.* In 2018 ieee 88th vehicular technology conference (vtc-fall) (pp. 1-5). IEEE.