OPPORTUNITIES AND THREATS OF EMPIRICAL RESEARCH ON SIGNAL CHANGE INTERVALS

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ABSTRACT

The performance of signalised intersections is determined to a large extent by the signal change intervals. The determination of an optimum duration of signal change intervals requires reliable data on the driver behaviour. The same applies to the development of realistic simulations of the driver behaviour during the signal change intervals. Up to date models still rely on kinematic models which do not sufficiently reflect the random characteristic of the underlying parameters or the factors influencing them systematically.

Results from empirical studies on driver behaviour depend to a large extent on the survey methodology and the specific situation of the surveys. It is unfeasible to take all factors influencing the driver behaviour into account at the same time. Conclusions from surveys consequently have to be interpreted with care. The empirical research conducted as part of a project on the influences of intergreen times on the capacity of signalised intersections (InSignIs; BOLTZE, WOLFERMANN 2009) and presented in this article underlines this observation.

This article summarises the opportunities and threats connected to empirical research. The awareness of data accuracy, general validity, and error sources is paramount to deduct adequate conclusions from empirical data. Special attention is paid to survey layout and stratified sampling. Examples underline the central statements.

INTRODUCTION

Background

The topic for this article arose out of empirical studies and the evaluation of former research conducted for a project, which analysed the capacity impacts of intergreen times (BOLTZE, WOLFERMANN 2009). Data diagrams given in the article are derived from this research project. Though many aspects mentioned can be transferred to empirical research on the traffic flow in general, the focus is directed at signal change intervals. The motivation for subsuming the opportunities and threats of such empirical research is outlined in the following section. The terminology and methodology for assessing signal change intervals, for conducting surveys, and for evaluating empirical data are outlined subsequently (p. 4 ff.), before the article expands upon possibilities to improve empirical research and findings based upon empirical data (p. 12 ff).. The gist of the article is summarised in the conclusions.

Why do we need empirical data?

Empirical data is required in the context of signal change intervals for the adequate (i.e. safe, efficient, and environment friendly) determination of yellow times and intergreen times, as well as for the development and calibration of simulations.

It seems obvious that signal programs are dependent on the traffic flow, which has to be described by parameters taken from observations, i.e. empirical data. The performance of signalised intersections in terms of safety, quality of traffic flow, capacity, and environment friendliness depends on the intersection and signal program design and its accordance with the traffic flow. The traffic flow is determined by a multitude of factors, as will be highlighted further down.

An issue discussed for a long time and still in the focus of researchers is the dilemma zone connected with the signal change. Yellow times have to be designed in a way that drivers can meet the correct decision out of the two options passing or stopping. Two risks are involved for the clearing vehicle: red-light running with the risk of right angle collisions in the intersection, and rear-end collisions on the approach. The reasons for the possible conflicts can be seen in either a driving behaviour not accounted for in the signal timing (late crossing) or a driver behaviour, not predicted by other drivers (in case of rear end collisions). While the driver behaviour will always fluctuate, a reliable assessment of the distribution is paramount in designing safe and efficient yellow intervals.

The duration of the signal change intervals is mainly determined by intergreen times. While yellow times are indicated to drivers to *influence* their behaviour, intergreen times are a part of the signal program which has to *reflect* the driver behaviour. Intergreen times are required for safety reasons, but they also influence significantly the capacity. Not only the intergreen times used, but also the procedures to determine them as laid out in manuals and standards are still partly based on experience and on simplifications. The consequences, in the positive as negative sense, are elucidated further below.

A review of research and codes of practice reveals, that particularly in the area of signal control, research is increasingly based on traffic simulations. While this procedure ostensibly avoids the strenuous collection of empirical data, the underlying simulations are only as good as the data with which they have been calibrated and validated.

What are the opportunities and threats of empirical research?

Empirical research, in this context the collection, processing, and analysis of data on the traffic flow at signalised intersections, requires high effort (cf. p. **Error! Bookmark not defined.** ff.), and is prone to errors (cf. p. 14 ff.). The following paragraphs will challenge this critical view by underlining the advantages of empirical research without neglecting the threats involved.

Effectiveness and efficiency of signal change intervals

Many transport engineers perceive a strict correlation of safety and the duration of intergreen times. Such an assumption, however, neglects the effect of compliance. Gratuitously long intergreen times reduce the driver compliance. This is particularly the case in connection with high saturation degrees. Figure 1 illustrates the driver behaviour at an approach with high saturation degree. About 25 % of vehicles are red-running. In this example, the saturation of the observed approach was very high, while the intersection was unoccupied during the signal change intervals. The intergreen time was consequently perceived by the drivers as being too long. The reluctance to run on red was diminished.

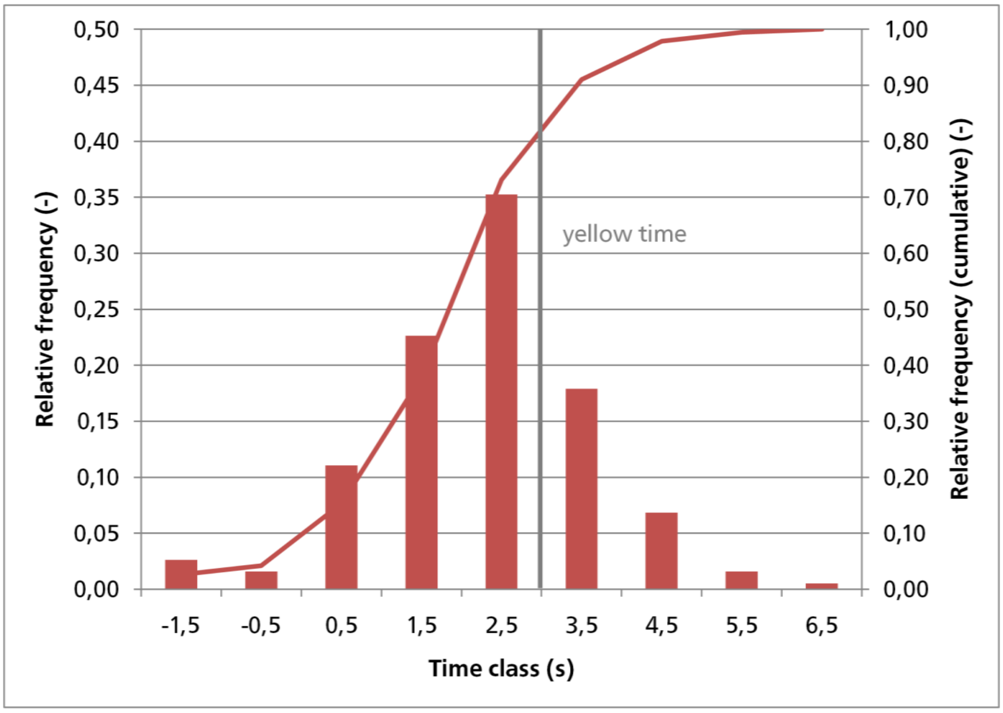

Figure 1 Crossing times (with reference to end of green; Source: Wolfermann 2009)

Recent research (BOLTZE, WOLFERMANN 2009) revealed that intergreen times, in addition to the safety issues discussed above, are not always efficient. It could be shown, that the capacity of signalised intersections is significantly reduced by signal change intervals. The part of this capacity reduction which is not justified by safety improvements reduces the efficiency of signal change intervals. While a significant part of the capacity improvement potential results from unlikely conflicts leading to very long intergreen times, a notable part stems from the neglect or simplified consideration of entering times. Not least, a detailed look at crossing times promises efficiency gains, too.

Simulations as a substitute for empirical research

Traffic simulations are calibrated for specific situations. Findings of research based on simulations cannot be generalised for deviating situations, if the underlying mechanisms are

not fully understood. Particularly the traffic flow at signalised intersections is in most simulations very simplified. Start-up lost times and crossing times are generalised without consideration of all the factors influencing them. An interaction of vehicles in the intersection (e.g. due to late clearing vehicles) or on the approach (e.g. resulting from the reaction to the yellow signal indication) so far cannot be simulated realistically. The complexity of driver behaviour and its influencing factors is outlined below to underline this statement.
The improvement of micro simulations to incorporate all processes and factors relevant for the assessment of signal change intervals still requires some research effort. A general approach to describe the traffic flow during signal change intervals, and a procedure to calibrate the underlying model with stratified empirical data (cf. p. 10 f.) is proposed in WOLFERMANN (2009).

Opportunities of empirical data and threats due to its evaluation

Two opportunities can be seen in basing research on empirical data: the safety and the efficiency (commonly also leading to environmental advantages) can be improved by detailed consideration of the real traffic flow. This can be achieved by more differentiated and less simplified signal change intervals as will be laid out later. Furthermore, empirical data, which is provided to the research community, can be used for manifold purposes, the improvement of traffic flow models and simulations being one of them.
Threats arising out of empirical research are the consequences of simplifications and assumptions, which are commonly unfeasible to avoid completely, and the also unavoidable data error. If simplifications lead to wrong findings, or if assumptions are not met, the researcher is prone to wrong conclusions. Errors can result from the random character of the traffic flow, from unsuitable sampling techniques, and from inaccuracies of the measurements. The article expands upon these issues after giving details on the used terminology, introducing a framework for describing and analysing driver behaviour, and a general overview on survey layouts.

SIGNAL CHANGE INTERVALS AND DRIVER BEHAVIOUR

Definitions and concepts behind signal change intervals

Conflicts and their dependence on signal program and intersection layout

The traffic flow at signalised intersections is divided into conflicting streams. A (vehicle) stream is defined by vehicles moving from an approach lane into a specific direction. At a four way intersection twelve streams can be distinguished (three possible directions at four approaches). Streams can use one or more lanes. On each lane one or more streams can be allowed. To divide the conflicting streams, the lanes they use are assigned to signal groups. Signal groups show the same signal indication at all times. Signal groups are combined to stages (AE: phases). In this way a hierarchy is created from stages as the principal element of signal programs which consist of signal groups, to lanes to which the signal groups are assigned, and down to streams on these lanes. Streams can be further separated according to vehicle type. The combination of stream and vehicle type is called a movement. This hierarchy is illustrated in Figure 2.

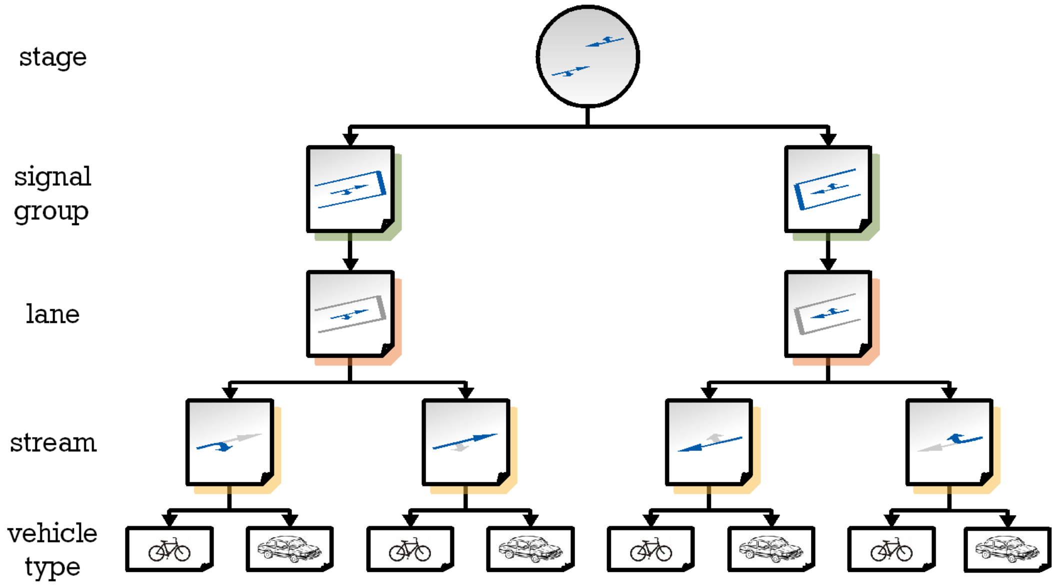

Figure 2 Illustration of the hierarchy of stage, signal group, lane, stream, and vehicle type

If a conflicting stage would simply start when the preceding stage ends, clearing vehicles of the ending stage and entering vehicles of the beginning stage would possibly meet each other in the intersection. The switch from one stage to another has consequently to be designed in a way to avoid such conflicts. This is the purpose of signal change intervals. Signal change intervals result from the shift of the beginning of a stage, so that all clearing vehicles have left all conflict areas in the intersection before entering vehicles arrive. Efficient signal changes achieve this aim in a way that the capacity reaches a maximum.

The shift is achieved by intergreen times, i.e. the interval between the ending of green of one signal group and the beginning of green of a subsequent conflicting signal group. The signal change is commonly announced by a transition time. Commonly a yellow interval is used for the change from green to red (sometimes preceded by flashing green or a countdown counter), and sometimes a red-and-yellow interval for the change from red to green (e.g. in Germany). Transition times are part of the intergreen time. If the intergreen time is longer than the transition time, an additional red-clearance time occurs. In extreme situations with long entering times, the intergreen time can be shorter than the yellow time. Depending on the intersection layout, particularly the location of signal heads (visible only on the assigned approach or also visible on crossing approaches), this raises safety concerns, which have not been analysed in detail for different conditions so far.

Elements to describe the traffic flow during signal change intervals

When looking at a specific conflict, the traffic flow can be distinguished between the behaviour of the last clearing vehicle and the behaviour of the first entering vehicle. This behaviour can be described by the time, the vehicle crosses the stop line with reference to the signal change (either from or to green), and by the time, the vehicle needs to cover the distance to the conflict area, i.e. the area of intersection of the trajectories of the clearing and entering vehicle. The former time is called crossing time $t_{cr}/t_{cr,e}$, the latter time is called clearance time t_{cl} or entering time t_e, depending on the process. The parameters are shown in a time-distance-diagram (Figure 3).

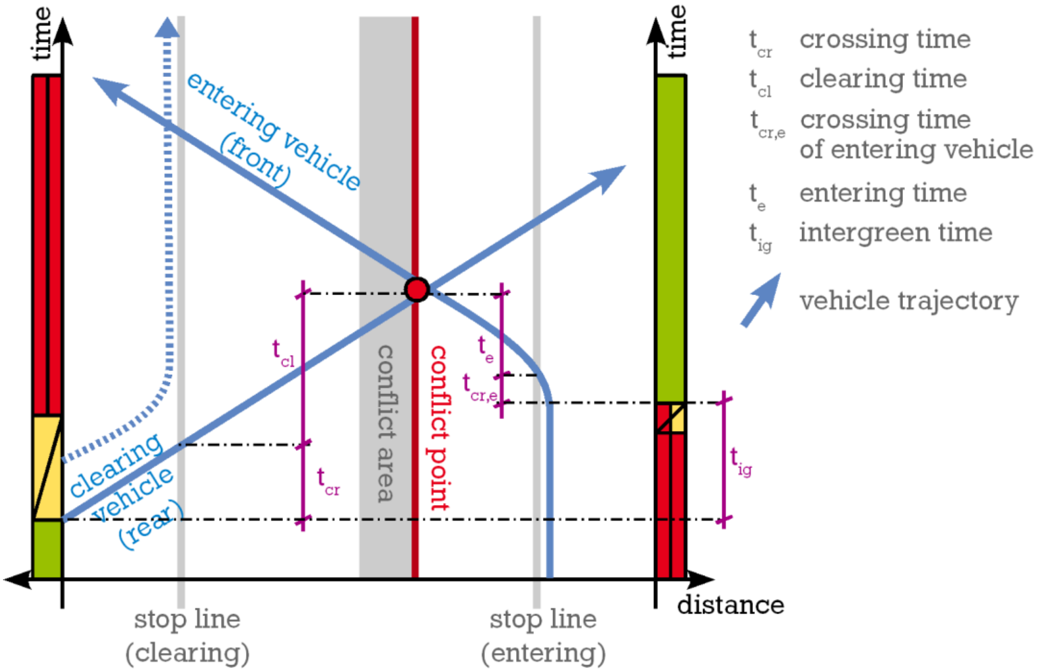

Figure 3 Illustration of traffic flow during signal change

Clearance and entering time depend on the distance of the conflict area from the stop line (in case of the clearing vehicle also on the vehicle length) and the speed of the respective vehicles. While clearing vehicles commonly do not change their speed significantly inside of the intersection, entering vehicles show different acceleration behaviour, depending on whether they came to a full stop at the stop line or not. The determination of the entering time depends significantly on the entering behaviour. Acceleration from a full stop leads commonly to significantly longer entering times.

Crossing times of clearing and entering vehicle, entering time, and clearance time describe the behaviour of the two vehicles irrespective of each other. Another parameter is needed to link the two movements. This parameter is the interval from the moment, the conflict area is left by the clearing vehicle, and the moment, the entering vehicle arrives there. This interval was termed post-encroachment time by Allen and Shin (1978).

If the post-encroachment time is sufficiently long, entering vehicles are not influenced by clearing vehicles. If, however, the post-encroachment time drops below a certain threshold, entering vehicles will adjust their behaviour due to clearing vehicles in the intersection. The delay caused to the entering vehicles is termed interaction time.

The challenge of analysing influences on driver behaviour

The parameters describing the traffic flow as outlined before depend on the behaviour of the participating vehicles' drivers. The driver behaviour is influenced by two groups of factors: individual factors and general factors. Individual factors are related to the (individual) driver, namely his disposition and his abilities or skills, and the (individual) vehicle. General factors result from the situation at the location and time under scrutiny. These general factors have an impact on the disposition of the driver, due to the physiological and psychological processes leading to the perception of the situation by the driver (e.g. stress by high speeds and low visibility). The general factors together define the situation, a driver experiences on his approach. This framework for the influences on the driver behaviour is illustrated in Figure 4.

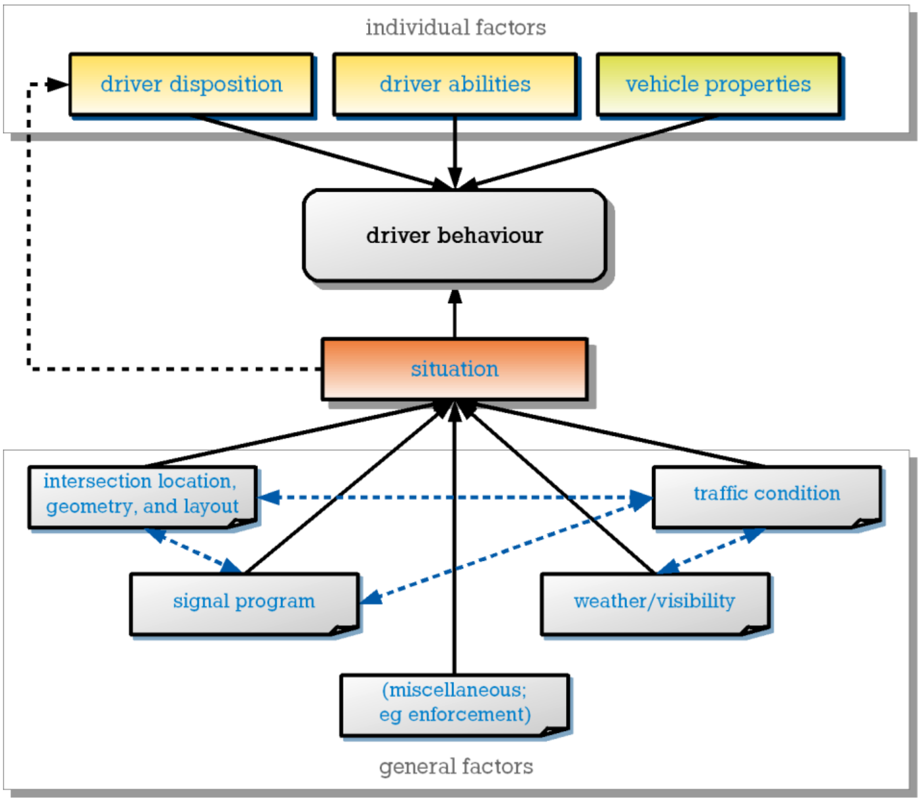

Figure 4 Influences on the driver behaviour

It is apparent that the mentioned factors, namely the individual factors, cannot, or not easily, be observed. Some cannot even be quantitatively described. Furthermore, the factors are not independent of each other (dotted lines in Figure 4). The traffic condition, for instance, depends on the intersection layout, the signal program, and the weather. It is therefore impossible to predict the driver behaviour precisely.

While Figure 4 gives a framework for the description of the influences on the driver behaviour, empirical research has to rely on parameters more easily to be observed. Since these parameters usually don't influence the driver behaviour directly, assumptions have to be made on the mechanisms behind the indirect influence. It is possible to derive the driver disposition to some extent from the situation. Short green times, for instance, connected with high traffic volumes commonly lead to higher stress.

Moreover, the situation, the driver disposition, and the driver abilities can be related to parameters easily observable. The time is probably the most important of these parameters. The traffic condition and the visibility are strongly correlated to the time of day. This correlation is often used to derive traffic conditions from the time. Rush hour observations, for instance, are commonly scheduled for a certain time of day. While the time is readily available, it has no or only a very limited *direct* influence on driver disposition or the situation. If the rush hour is shifted or extended due to bad weather or such, the time of day is no longer a reliable parameter to derive the traffic condition.

The example of the time highlights the dilemma empirical research is facing. The parameters needed to get meaningful results can in many cases not be measured or the measurement is not feasible. The research has to be based on indirect relationships. The models and assumptions used can vary significantly, making direct comparisons difficult. Comprehensive studies are nearly impossible to achieve. Even though several factors can be considered, it remains challenging to determine even "simple" parameters like the capacity of signalised intersections accurately (cf. MESSER AND BONNESON 1997). One possible solution to this dilemma could be the direct consideration of human factors, as has been done by, for instance, LONG 2007.

SURVEY LAYOUT AND STRATIFIED SAMPLING

Survey Layout

Empirical research on signal change intervals can be based on different survey layouts, depending on the aims and factors under scrutiny, the desired accuracy, and the general applicability of the findings. The survey layout comprises the survey technique (measurement devices, data processing, etc.) and the survey location and time, which determine the sample size. Finally, the time horizon (peak hour, weeks, months, years) and the comparison of data sets for the assessment of measures (study sample and control sample) lead to different survey layouts.

Survey techniques

As has been outlined before, the most important parameters to describe the traffic flow during signal change intervals are times. Depending on the underlying model, speeds and distances can become equally important. Which dynamic parameters have to be obtained in addition to these primary ones, depends on the exact survey subject. Traffic volumes according to vehicle types and travel directions are among them in most cases. The mentioned parameters limit the choice of survey technology. Most available detectors do not fulfil the requirements on the precision. They may not be able to detect speeds, or they can only be applied to certain lanes. Often a combination of detectors or measurement devices can be used to reduce the amount of data that has to be collected manually.

Though survey techniques vary, a general trend can be observed. Most data is obtained by manual counts using time recorders. Recent studies transfer the data gathering into the office by taking videos first and evaluating them later. Image processing software increasingly penetrates the market, which leads to automatic data generation. Image processing is still limited by the high requirements on angle of view, environmental influences (visibility, precipitation, wind), and achievable accuracy. Manual counts, on the other hand, are affected by human error. Human error in properly realised manual measurements is generally perceived as being sufficiently small (cf. e.g. LI AND PREVEDOUROS 2002, TONG AND HUNG 2002, NOYCE ET AL. 2000). This assumption is supported by comparative tests for video evaluations conducted at Technische Universität Darmstadt (TODT 2009). While it is proven that a high accuracy can be achieved, due diligence is required to realise it. Human error is an issue in manual data acquisition, particularly since it is usually impossible to detect or assess it retrospectively.

Part of the survey technique is the definition of terms and the exact location of measurements. For some parameters standardised procedures are proposed in manuals like the U.S. Highway Capacity Manual. Depending on the survey's purpose, deviations from these standards are widely applied. The measurement of headways, for instance, can be derived from the passage of front or rear bumpers of vehicles, or from the passage of axles. This also applies to distance measurements, where the stop line, the curb line, or other locations in the intersection can be used as a reference. LI AND PREVEDOUROS 2002 point into this direction by underlining the misleading term "clearance of intersection". If the front axle of a vehicle is used as the reference point, the rear of the vehicle may still be inside of the intersection. If the rear of vehicles is used, the length of vehicles has a different role than when using the vehicle front. A clear statement of the definitions used is indispensable. The definitions given above provide a framework for reference.

Sample size

A big difference can be seen in the amount of data obtained, both qualitatively (i.e. the number of parameters observed) and quantitatively (i.e. the sample size and number of intersections/approaches observed). While some surveys focus on the peak hours at a few intersections accumulating only about 100 data sets, other studies comprise more than ten intersections, observe the traffic flow over long periods, and reach sample sizes of several thousand data sets.

One reason for big studies is the approach to overcome causal shortcomings by statistical methods. If cause-and-effect analyses are difficult or prone to wrong conclusions due to biased samples, statistical methods can be used to obtain meaningful results (statistical inference). While statistical methods are in many cases the best option available and while they give usually good indications on underlying mechanisms, they nevertheless have to be distinguished from cause-and-effect relationships.

Time horizon and control groups

To assess measures, two methodologies are commonly applied: a comparison of study intersections with control intersections, or before-and-after studies. Both procedures can be combined. While the first procedure is less promising due to the difficulty in finding suitable "control" intersections, the second procedure requires high effort for the data collection and is affected by external changes which are not part of a measure. Whether an intersection can be used as a control intersection depends on various factors as has been outlined above. How long drivers need for a habituation to new circumstance appears to differ. HORST AND WILMINK 1986 observed a period of six months after which no more changes in driver behaviour could be observed during a long term study, while they state HULSCHER 1980 with periods exceeding this time significantly.

Stratified sampling and sample size

It is not the aim of this article to provide an introduction into statistics as can be found in numerous better suited publications. Rather key aspects are pointed out as a basis for the development of improvements for empirical research on signal change intervals.
Both capacity and safety models are based on parameters, for which empirical data has to be gathered. This data is in most cases randomly distributed. While for capacity impacts the averages are of primary importance, for safety models the variance and extreme values have to be considered, too. Both, the mean and the spread of the population depend on the influencing factors outlined on pages 7 ff. Surveys stratified to some of these factors help to keep the required sample size feasibly small and reduce the variation of the sample data.

Stratified sampling

While most models naturally consider the variance of parameter distributions, the reasons for the variance are not always analysed. Two kinds of variation have to be distinguished: the variance of the population for a specific situation, which results from the random variation of the traffic flow, and the variance among different situations, resulting from a change of influencing factors.
Figure 5 illustrates the difference. Shown are the clearance speeds at approaches to signalised intersections under different situations. The red columns give the clearance speeds stratified for non-coordinated approaches. The green columns depict the speeds stratified for coordinated approaches. The distribution of all speed measurements is shown in blue. It can be seen that not only the median, but also the variance of the total sample varies significantly from the variance of the two stratified samples.

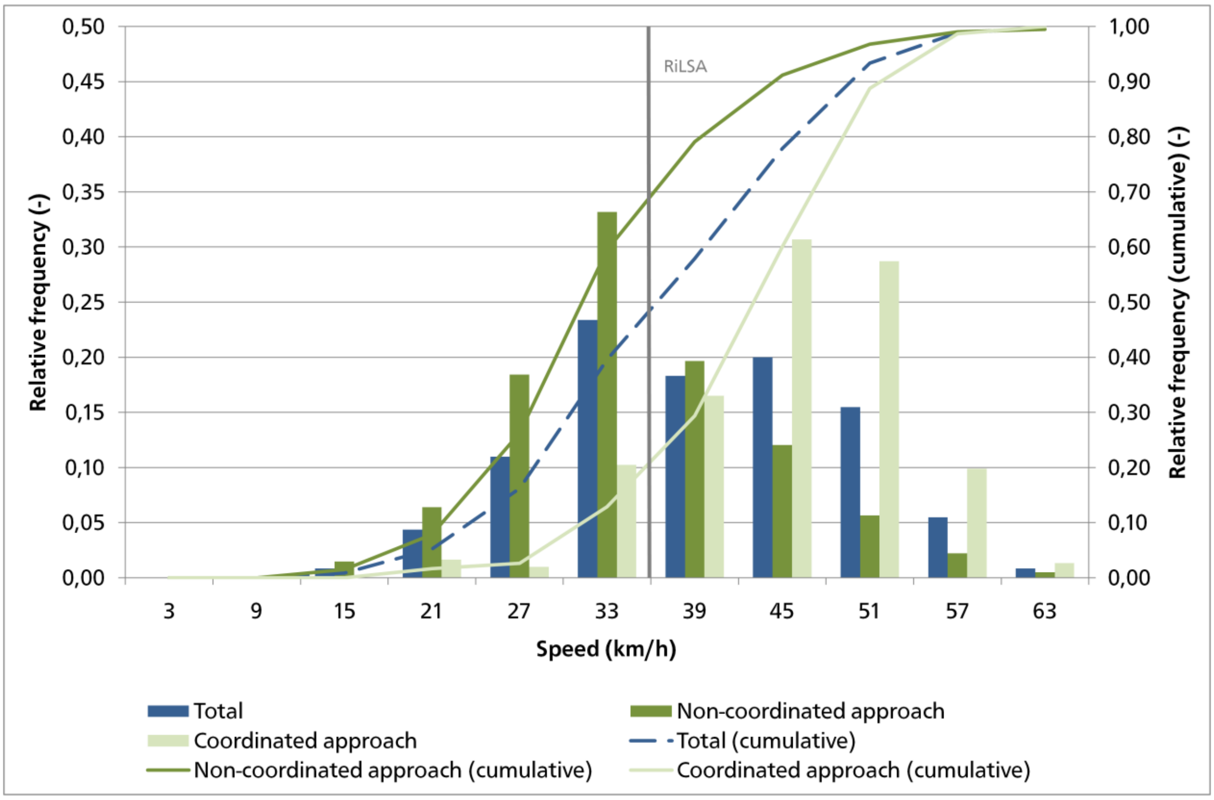

Figure 5 Stratified sampling for clearance speeds (WOLFERMANN 2009)

While the traffic flow will always vary, the knowledge and determination of the factors influencing the driver behaviour can help to significantly improve the quality of models by stratified sampling. On the other hand, it has to be taken into account, that a survey conducted for a specific situation will underestimate the total variation of outcomes for all situations. If in the above example the influence of coordination on clearance speeds is neglected and a survey is conducted only at non-coordinated approaches, conclusions drawn for all approaches will be inadequate for coordinated approaches.

Sample size

The sample size is of major importance for the accuracy of empirical data. Due to the manifold influencing factors no required sample size can be determined. Only a desired level of accuracy can be defined, which is only reached with a sufficient sample size. The sample variation (s), however, depends not only on the sample size (n), but also on the underlying variation of the population. Since in most cases the latter is unknown, it cannot be determined which part of the variation results from the sample error. An estimator commonly used for the mean of a sample is the standard error ($SE = \frac{s}{\sqrt{n}}$).

The required sample size may be significantly reduced by stratified sampling. Particular attention has to be paid, however, on the definition of the strata (subpopulations). Even if only particular factors are to be analysed, other factors cannot be neglected. In the example given in Figure 5, the given sample distributions not only depend on the coordination, they will also depend on other factors like saturation degree, cruising speed and so forth. These other factors have to be the same for both stratified samples, or a sample error is introduced. The required sample size depends, hence, significantly on the influencing factors. Only a thorough survey design helps to reduce this sample error.

IMPROVING STRENGTHS AND REDUCING WEAKNESSES OF EMPIRICAL RESEARCH ON SIGNALISED INTERSECTIONS

Impact of variance and inaccurate average estimates on safety and capacity

The role of variance of signal change relevant parameters

Safety models have to take extreme behaviour into account. Behaviour deviating from the mean is often more important than the mean itself. Most of the parameters relevant for the determination of signal change intervals are randomly distributed variables. The variance depicts how much values deviate from the mean.

To account for the variation of the traffic flow in safety models, safety margins are introduced. The more the underlying parameters vary, the greater the safety margin has to be to achieve the same safety level. Safety margins, on the other hand, lead usually to reduced efficiency in terms of capacity. As has been highlighted before, long signal change intervals may also lead to less compliance. For both reasons safety margins should be as small as strictly necessary. If the variance of the parameters underlying a safety model can be reduced, the safety margins can be reduced, too. Furthermore, the less the behaviour varies, the better the behaviour of drivers becomes predictable for other drivers. By reducing the variance of driver behaviour, the likeliness of conflicts can be reduced.

The latter point requires an influence on the driver behaviour itself. The first points, however, refer to the variance of the model parameters. As has been outlined before, this variance depends not only on the variation of the total population, but also on the measurement and sample error. Stratified sampling is consequently a useful tool to reduce the variance of model parameters. The threats involved in stratified sampling also have been highlighted before. Stratified sampling, as a conclusion, is an opportunity if conducted properly and with due diligence. For which parameters a stratified sampling appears profitable is outlined on pages 13 ff.

The role of average values of parameters

Average values of parameters describing the traffic flow are of primary importance for capacity calculations. The cycle time and green split are commonly based on average values. Erroneous averages consequently lead to inefficient signal timings. While this has only minor impact on the safety (e.g. due to unnecessary high saturation degrees and reduced compliance), it has a major impact on environmental issues and the travel times.

In the context of signal change intervals, average values of the start-up lost times and the green time extensions (i.e. crossing times of clearing vehicles) are required to compute effective green times. Effective green times are needed to get accurate capacity estimates. A distinction of signalled and effective green times is particularly important for short green intervals, where the signal change has a major impact on the capacity. While the U.S. Highway Capacity Manual recommends to assume equal start-up lost times and green time extensions, surveys in Germany indicate a difference of the two towards higher green time extensions (BOLTZE, WOLFERMANN 2009). A difference of only one second for a ten second stage leads to a 10 % capacity increase – a significant margin. Nevertheless, effective green times are not taken into account so far in the German Highway Capacity Manual (FGSV 2001).

The adjustment of saturation flow rates, which depend to some extent on the signal change intervals, is a kind of stratified sampling. The opportunities and threats resulting from stratified sampling also apply to average parameter values and, thus, to capacity estimates.

Parameters of primary relevance for model accuracy

Surveys at urban signalised intersections conducted for the project "Influence of Intergreen Times on the Capacity of Signalised Intersections" (InSignIs, BOLTZE, WOLFERMANN 2009) aimed at identifying parameters of primary concern for adequate intergreen times and accurate capacity estimates at signalised intersections. While the number of observed intersections and lanes is not sufficient for general quantitative conclusions, it gives a valuable indication on the magnitude of the variation of different parameters. Noteworthy is the variation at a single approach lane in comparison to the variation between different lanes. The most striking observation is the low variance for specific lanes, but the significant differences between different intersections, which underlines the opportunities and threats of (intentionally or unintentionally) stratified sampling.

Three parameters deserve particular attention: clearance times (due to the high variation of clearance speeds, cf. Figure 5 on page 11), crossing times of clearing vehicles (Table 1), and entering times (Figure 6). The following tables and figures give the average values, the standard deviation, the standard error (based on the standard deviation and the sample size), and the sample size for measurements during the peak hours at approach lanes of different intersections in the city of Darmstadt, Germany.

Crossing times

Table 1 Crossing times of clearing vehicles (WOLFERMANN 2009)

Parameter	Unit	Lane 1	Lane 2
Average crossing time	(s)	2.2	1.6
Standard deviation	(s)	1.4	1.6
Standard error	(s)	0.1	0.2
Sample size	(-)	192	57

Table 1 shows the very small standard error of crossing times, the high standard deviation (coefficient of variation 60-100 %), and the significant difference of the averages between the measured lanes from two different intersections. The crossing times, hence, can vary notably even at single approach lanes, but the average can be predicted quite accurately, if stratified sampling is used.

Entering behaviour

The entering time deserves particular attention due to the two general situations: vehicles can cross at the onset of green with positive speed (moving start), or they come to a full stop during the red interval and have to accelerate at the onset of green. The first case is rare, particularly for saturated and non-coordinated approaches. The second case leads to significant entering times (Figure 6). The consideration of entering times can help to reduce the signal change interval duration notably, if the first case can be excluded safely.

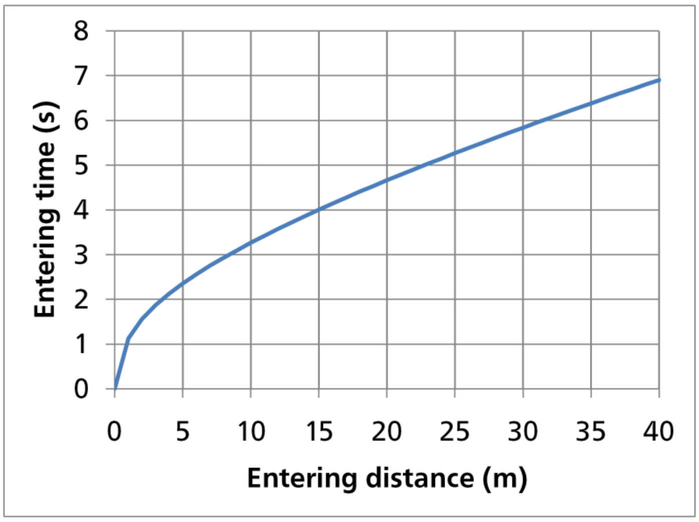

Figure 6 Entering times for acceleration from full stop
(averaged for 1781 single speed measurements, 5 intersections, WOLFERMANN 2009)

Sources of error and how they can be reduced

Sampling error

Empirical data is based on samples. The sample distribution varies from the population distribution. It is furthermore influenced by measurement errors and sampling errors. Sampling errors occur if the sample is not representative for the population. The population in case of signal change intervals depends on the influencing factors. The more general applicable a model is meant to be, the more diverse the population will be. Surveys conducted under specific situations (limited number of intersections, limited survey time, etc.) will consequently introduce a sampling error, if general results are derived.
The example in Figure 5 highlights this conclusion. A survey conducted at a coordinated approach will deliver very inaccurate results for non-coordinated approaches. While this sampling error cannot be avoided completely due to the manifold influencing factors, the

awareness of its possible existence is of salient importance when comparing survey results and deriving conclusions from empirical data.

Measurement error

The measurement error depends on the used technology and evaluation technique. While this is well known, empirical research rarely assesses the measurement error. The reason can to a large extent be found in the high effort required to determine the measurement error. The determination of the measurement error requires control measurements, which on site are difficult to conduct. Commonly only one measurement method is deployed without control measurements. While the factors influencing the measurement error depend on the survey technique, the relevance of measurement errors depends on the model, for which the data was obtained.

Error propagation

Error propagation has to be taken into account when considering model accuracy. Saturation headways, for instance, do not vary much if measured properly, as can be seen in Table 2 (coefficient of variation about 25 %). If they are used to calculate saturation flow rates and start-up lost times, however, small errors sum up and can easily reach significant values. It is, hence, advisable to measure longer time intervals and divide by the number of vehicles observed instead of measuring single vehicles separately.

Table 2 Saturation headways at urban intersections (WOLFERMANN 2009)

Parameter	Unit	Lane 1	Lane 2	Lane 3
Saturation headway h_s	(s)	1.9	2.0	1.8
Standard deviation of h_s	(s)	0.5	0.5	0.4
Number of headways	(-)	248	297	124

Reducing sources of error

To reduce the error of surveys, it is of salient importance to be aware of them. During each stage of a survey the possible error sources should be analysed. Sound surveys are not based on the availability of measurement devices only, they have to be based on a comprehensive assessment of options with their influences on data accuracy. If possible, control measurements should be conducted. Measurements taken under similar conditions have to be compared to each other to check for systematic errors. If data of one stratum differs significantly from data taken at another time or location for (ostensibly) the same stratum, the stratification should be reconsidered. When processing the data, error propagation should be taken into account. The total error may be reduced by adjusting survey layout and data processing to the error propagation.

CONCLUSIONS

Empirical studies are an indispensable element of traffic engineering and transport planning. While models can be assessed with the help of simulations, the assessment is always only as good as the simulation itself, which has to be calibrated and validated – with reference to empirical data. This article focuses primarily on signal change intervals, but some observations can be transferred to other areas as well.

The opportunities of sound empirical research are manifold. Safety and efficiency of signal programs can be significantly improved, if the parameters used are derived from reliable data. A major reason is the complex relationship between safety and signal change intervals. Not in all situations “safety margins” lead to improved safety. Safety margins, however, in most cases reduce the efficiency of signalised intersections.

Sound empirical research requires a thorough survey layout. The more general the conclusions drawn from the data should be, the more effort is necessary. A way to improve the accuracy of the data is the stratification of samples. Stratified sampling can reduce the variation of the data significantly. While many parameters, which are of importance for the determination of signal change intervals, vary only slightly at single intersections, they differ significantly between different intersections. This fact can be used to improve the accuracy of the data without bigger sample size. Parameter distributions with small variance lead to smaller safety margins, which improves the efficiency of signalised intersections. Stratified sampling, on the other hand, threatens the explanatory power of surveys. The strata have to be thoroughly defined, and the survey layout has to precisely meet the requirements of the stratification. Parameters of particular interest for stratified sampling are the crossing times of clearing vehicles, clearance speeds, and entering times.

In many cases video evaluation is the most feasible option for surveys at signalised intersections. The procedure proved to be efficient and accurate. As for all measurement techniques, the possible error sources have to be considered. The impact of erroneous data should be assessed by analysing the error propagation. Accumulated parameters can easily lead to significant errors in the model output, despite a low variance of the input data.

The knowledge of possible influencing factors on the driver behaviour, the thorough assessment of the survey technique, and an evaluation of the model used with all the assumptions on which it is based, are paramount to reach sensible and reliable conclusions from empirical research. This article addressed the opportunities in following this guideline, the threats, if it is ignored, as well as the details on how opportunities can be exploited and threats avoided.

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