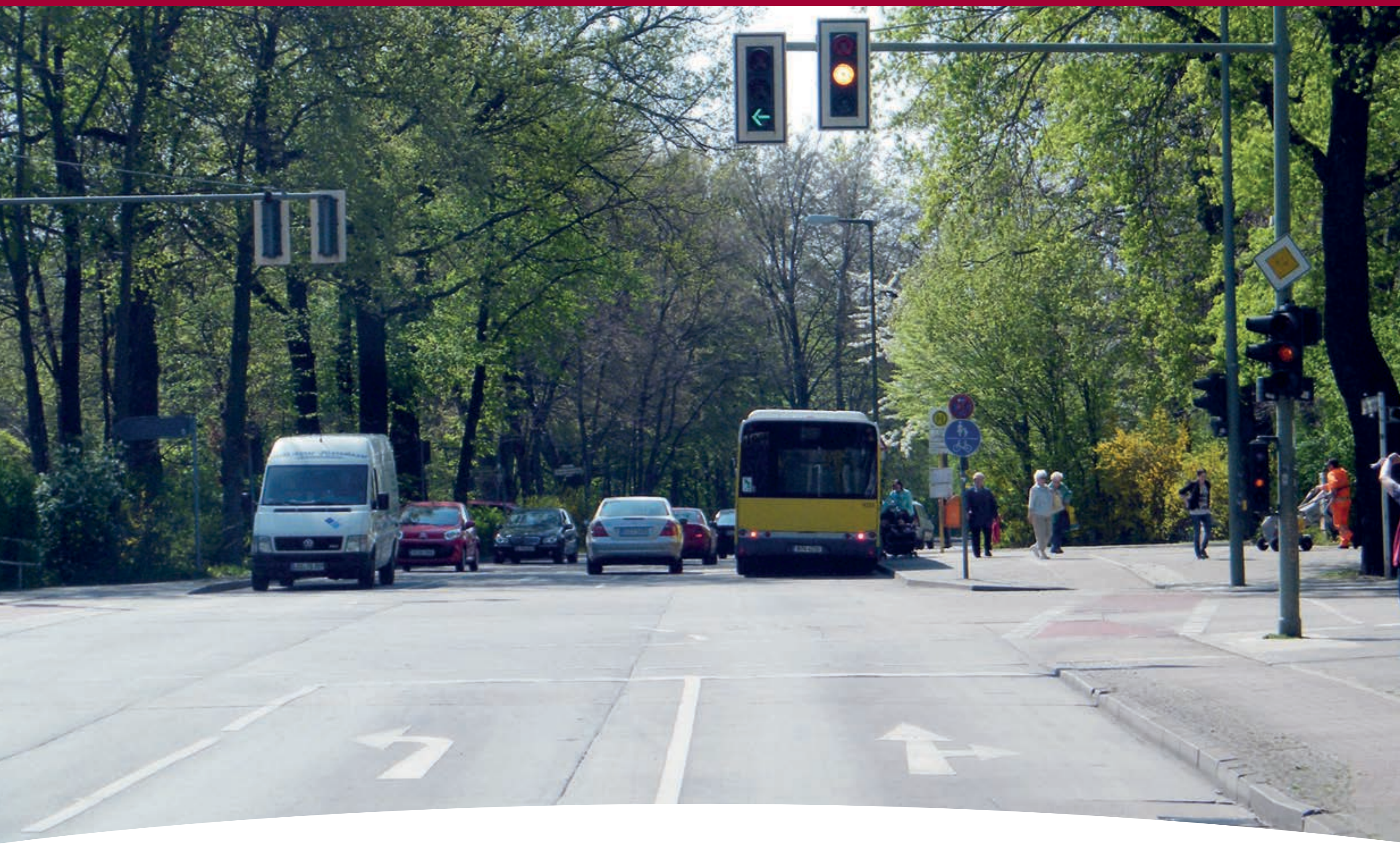
German Insurance Association No. 19



Compact accident research

The impact on traffic of the special left-turn phase at signal-controlled intersections

Unfallforschung der Versicherer
GDV

Imprint

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German Insurers Accident Research

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Published: 10/2010

Preliminary remarks

Serious accidents regularly occur at intersections controlled by traffic signals, both inside and outside of urban areas, when traffic turning left (across the oncoming traffic) collides with oncoming traffic or with pedestrians or cyclists who have been released in parallel. According to calculations by the UDV, accident costs are halved if a separate signal phase for traffic turning left is introduced. Decision-makers, however, often resist such moves, as they claim that this slows down the flow of traffic. The UDV therefore commissioned a study from the Technische Universität Dresden to determine whether this argument is valid. Simulation of a wide range of types of intersection and traffic signal phases showed that an additional protected green phase for traffic turning left generally resulted in no relevant restrictions to the capacity of the intersection.

Content

1 Introduction and objective

Intersections in the road network can be constructed and operated in different ways. The combination of the construction and the way in which the traffic is regulated is referred to as the intersection type (Eckstein/Meewes 2002 and Draft Guideline for Designing Roads outside of Built-up Areas, RAL).

At locations with a high volume of traffic, intersections regulated by right-of-way are as a rule being replaced by intersections regulated by traffic signals. Traffic signals make the road space within an intersection available to the competing streams of traffic alternately in a cyclic sequence (phase sequence). The different streams of traffic then cross the intersection in sequence. If a free-flow solution or a roundabout cannot be considered, intersections and junctions controlled by traffic signals are regarded as intersection types that provide both high capacity and a high level of traffic safety. Studies have, however, shown significant discrepancies in this view: Traffic signal control does not always make an intersection safer than control on the basis of right-of-way, as it is possible that initially there is only a change in the structure of the safety deficiencies, depending on the type of control and the number of phases, but that there is no resulting improvement in traffic safety.

According to the German Guidelines for Traffic Signals (RiLSA 2010), traffic signals are installed to "increase traffic safety and/or to improve traffic flow quality. [...] The set-up of a traffic signal system has to be considered if accidents which may have been prevented by traffic signal control have occurred repeatedly and if alternative measures (such as speed limits, overtaking prohibitions or constructional crossing aids to pedestrians or cyclists) have proved to be ineffective or not promising." According to Section 37 of the German "General Administrative Regulations on the Road Traffic Regulations" (VwV-StVO), situations in which traffic signals are necessary include those where accidents frequently happen because visibility is restricted and there is no possibility of improving visibility or prohibiting traffic which is crossing or entering the road, and those where there are frequent infringements of right-of-way without this being related to the intersection being difficult to identify or with the right-of-way being difficult to understand. The VwV-StVO also states that the following principles apply to sections 39 through 43: "The free flow of traffic is to be upheld using the means available. In applying this principle, the safety of all road users takes priority over the free flow of traffic."

This study is therefore intended to clarify the impact on traffic caused by different traffic signal control methods deployed to protect traffic turning left. In particular, it is intended to show the extent to which any claimed negative impact on traffic flow actually occurs and how it can be minimized or offset by an improvement in traffic safety.

The study was carried out by the Faculty of Transportation and Traffic Sciences, Traffic Engineering department at the Technische Universität Dresden, under Professor Reinhold Maier.

2 Traffic turning left at signal-controlled intersections

2.1 Non-conflicting and conflicting flows

"The individual components, as for example the actual layout of the intersection, the division of approaches into lanes, the direction of pedestrians and cyclists and the signalisation of the individual traffic streams have to be coordinated in such a way that the preconditions for safe traffic flow are given under all operational conditions and for all traffic loads." (See RiLSA 2010, Section 1.1.) Traffic turning left at intersections controlled by traffic signals can be handled in different ways. Traffic streams which do not share any joint conflict areas are to be regarded as ***non-conflicting*** streams and can therefore be released together in a single phase. If individual traffic streams share any joint conflict areas, they are termed ***conflicting*** traffic streams. They are released separately. Turning traffic that is not subject to special signal control is an exception in this context. Such streams are termed ***partially conflicting*** streams in RiLSA.

2.2 Traffic turning left as conflicting streams

Because traffic turning left shares joint conflict areas with both oncoming traffic and with pedestrians and cyclists travelling in the same direction, they are in principle seen as conflicting flows and must be released in different phases. They are only classified as signal protected if all streams that conflict with them are blocked while they are released. If this approach is adopted, it results in multi-phase controllers in which through traffic and traffic which is turning is released alternately.

2.3 Traffic turning left as partially conflicting streams

Whereas non-conflicting streams can be combined in a single phase, conflicting traffic streams must always be subject to separate signal control. Turning traffic streams are an exception in this respect: They can be handled without signal protection at the same time as through traffic. The priority regulations laid down in Section 9 paragraphs 3 and 4 of the German Road Traffic Regulations StVO apply here. In the guidelines, streams of turning traffic such as this that are not subject to special signal control are referred to as partially conflicting streams. These streams of turning traffic must observe the priority of the parallel (pedestrian and cyclist) stream and pass through the oncoming stream of traffic, i.e. the individual road user decides what length of gap in the higher priority stream they accept or reject.

If the release of traffic streams turning left is divided into a "protected" and an "unprotected" period, this is referred to as "temporarily protected release". A distinction is made between "leading green" and "lagging green" which are defined as a time by which the release time for one or more traffic streams starts earlier or finishes later than for other traffic streams released during the same phase (RiLSA 2010). These times can in principle be programmed with or without visual indication using an auxiliary signal. If such times are indicated, a green arrow is used for the protected release time and an amber flashing signal is used for the release time in which the traffic must pass through oncoming traffic. Leading green with no indication is regarded as unacceptable for reasons of safety, and lagging green with no indication is not recommended as it is difficult for drivers to estimate the relevant times.

2.4 Selecting cases for investigation

The following criteria were established for the cases for investigation:

- Intersections with single-lane guidance of through traffic in all directions.
- No influence of non-motorized users guided in parallel. Taking account of pedestrians and cyclists would have a negative impact on the quality of traffic flow in the event of unprotected release[1).]
- No significant longitudinal inclination, no unusual lane widths and no unusually large or small turning radii.

2.5 Initial conditions for the calculations

Simulations were performed to compare the different control variants. The following input parameters from the current guidelines and recent research results were used:

- Cycle time t_C = 60 s,
- Transition time calculation as per RiLSA 1992[2)],
- Speeds on the approach v = 70 kph and hence amber transition times of 5 s,
- No movement on amber if the vehicle is more than 10 m before the stop line when the amber phase starts,
- Saturation traffic volumes of q_S = 2000 vehicles/h for through traffic, q_S = 1950 vehicles/h (t_F > 10 s) or q_S = 1900 vehicles/h (t_F: 6-10 s) for traffic turning left and q_S = 1800 vehicles/h for traffic turning right, q_S = 1700 vehicles/h for temporarily protected traffic turning left,
- Critical and follow-up time gaps for traffic turning left through oncoming traffic of 5.9 s and 2.5 s without provisions for turning right and 6.4 s and 3.0 s with provisions for turning right,
- No heavy goods traffic, only private car streams and
- No non-motorized road users.

The different types of intersection were simulated with different control variants. Each signaling variant was simulated with six different random seed numbers.

In the case of a fixed release time, the traffic volumes of the higher priority traffic turning right and through traffic were gradually reduced, starting from the maximum inflow on all lanes (1000 vehicles/(h*lanes)). This results in larger time gaps that can be used by traffic turning left when the time gap becomes large enough. Initially, the maximum traffic volume without the influence of traffic turning left was determined (basic intersection capacity) and then progressively reduced to the proportions 0.8 - 0.6 - 0.5 - 0.4 - 0.3 - 0.2 - 0.1 - 0.0. The case "no through traffic or traffic turning right" is used to (theoretically) determine the maximum volume for traffic turning left.

In the case of a variable release time, the traffic volumes for through traffic and traffic turning right were not changed. To obtain a saturated state in every cycle, the inflowing traffic volumes were set to 1000 vehicles/h for each lane for all types of traffic stream. Initially, a minimum release time for traffic turning left of t_F = 5 s was taken, resulting in

1) When traffic turning left is protected by a separate green phase, there is no pedestrian or cyclist traffic released in parallel. In contrast, in the case of unprotected traffic turning left, pedestrian/cyclist streams have a negative impact in capacity, depending on the volume of traffic. This means that the results would have been skewed in favor of the secured turning phases. In order to ensure that the two types of signal control remained comparable, however, and to represent operating times and intersection types with little or no pedestrian/cyclist traffic, the effect of non-motorized traffic was not accounted for.

2) Taking into account the implementation in practice, where the release time does not start before the end of the amber time. At the time of the study, the old 1992 Guideline was still applicable.

a maximum release time for through traffic and traffic turning right. The release time for traffic turning left was then progressively increased by 2 s up to the maximum. The release times for the higher priority oncoming traffic always range between the maximum and minimum release time of $t_{F,min}$ = 5 s as per RiLSA. The cases "no traffic turning left" and "no traffic turning right/through traffic" were used to determine the theoretical values for the maximum outflow volumes.

2.6 Results of the simulation calculations

2.6.1 Large intersection with triangular islands (case 6)

We shall investigate an intersection with three lanes on all approaches. Traffic turning right flows away freely alongside the triangular island. In the case of signal protection for traffic turning left, this stream of traffic turning right is, however, also protected (exception: "diagonal arrow" with leading green or lagging green).

On the basis of the size of the intersection, the simulations assume a cycle time t_U = 90 s. If all approaches to the intersection are used to their full capacity, this results in a release time t_F = 39 s for through traffic and traffic turning right, giving a maximum volume of through traffic of 815 vehicles/h (traffic turning to the right freely flows away independently of this). Figure 1 shows the volume of oncoming traffic (through traffic) relative to the increase in the volume of traffic turning left for different phase systems and methods of regulating traffic turning left.

In the case of simple ***two-phase control***, there is no separate protected time for traffic turning left. This means that traffic turning left will tend to flow away during phase changes.

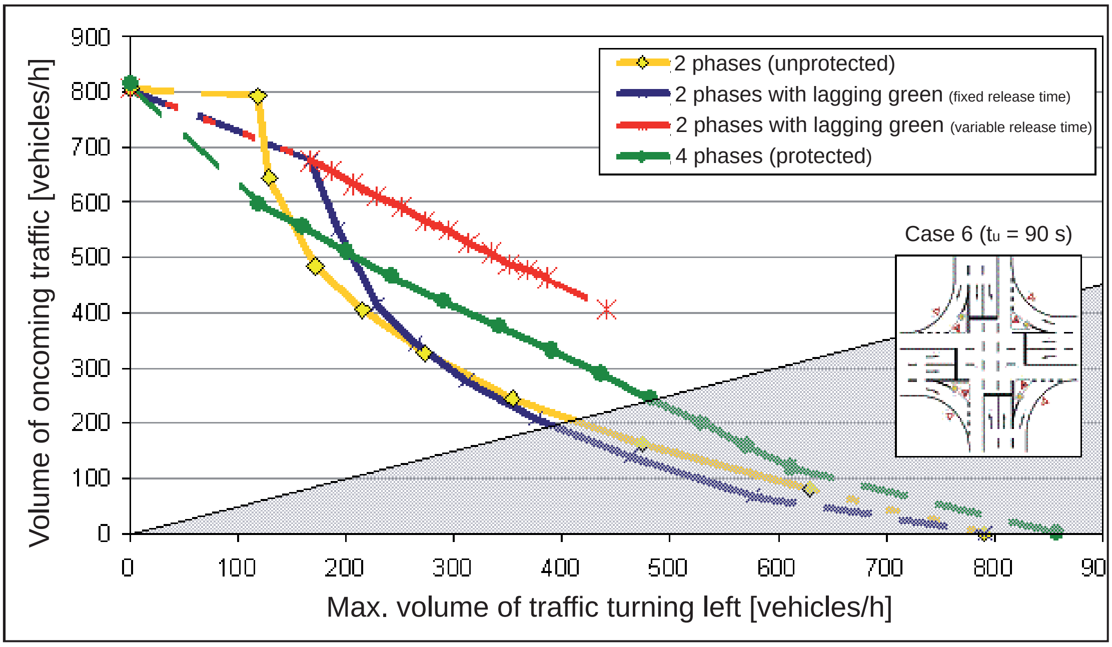

Figure 1:
Comparison of the influence of a conflicting vehicle turning left using different control methods for traffic turning left on the maximum volume of higher priority through traffic for large intersections with triangular islands and a cycle time of 90 s.

This shows that up to three vehicles can flow away per cycle at the maximum volume of oncoming traffic. Because of the geometrical size of the intersection, these vehicles will have waited in the interior of the intersection. This results in a maximum volume of traffic turning left of approximately 120 vehicles/h given the maximum volume of traffic in the opposite direction. A significant increase in the volume of traffic turning left can only be observed if the volume of traffic in the opposite direction falls to below 400 to 500 vehicles/h: At a volume of 400 vehicles in the opposite direction, approximately 215 vehicles can flow away to the left, i.e. approximately 100 vehicles/h manage to find sufficiently large time gaps in the oncoming traffic. If the volume of through traffic falls still further, even more traffic is able to flow away to the left. However, if the volume of traffic turning left is greater than that of the through traffic stream or oncoming traffic stream, in which case the traffic turning to the right freely in case 6 must also be taken into account, the intersection geometry or the control type will generally be changed, because the traffic turning left would then become the dominant stream and would be assigned more than one lane, for instance, or the intersection would be redesigned. The curves shown in the hatched area are therefore not regarded as significant, in particular not for the unprotected release of traffic turning left.

If a **leading green or lagging green** is implemented in a two-phase control system, this time is not available for the oncoming traffic in the course of the cycle. This causes the volume of oncoming traffic to be reduced while at the same time increasing the volume of traffic turning left. The results for leading green and lagging green differ only slightly. If the additional release time for traffic turning left is restricted to a set duration, the potential volume of oncoming traffic falls rapidly as of approximately 700 vehicles/h, as the release time must be reduced to 28 s.

In the case of **variable leading green/lagging green**, the curves are extended in favor of the volume of traffic turning left as shown in Figure 1. In terms of capacity, the results for leading green are somewhat more favorable than for lagging green, because even when the diagonal green arrow appears, traffic turning left does not move off immediately, whereas in the case of leading green, traffic turning left moves off immediately the release time begins.

In the case of protected release on all approaches **(4-phase control**), it is assumed that the phase for traffic turning left is activated depending on traffic conditions. The phase is used very often at the high-volume intersection under investigation. If phases for traffic turning left are only demanded sporadically when there is a low volume of traffic turning left, intermediate values of anything up to complete utilization of the release times for oncoming through traffic arise at values below 120 vehicles turning left per hour. Such cases should only occur rarely in reality, because special phases for traffic turning left are regularly incorporated, even if no demand has been registered by the detector, as the possibility cannot be excluded that vehicles have not been detected by the sensor. The more frequently left-turn phases are demanded and granted, the greater the reduction in the volume of oncoming traffic as a result of the changed release times. The difference in total capacity, however, shows that at volumes of traffic turning left significantly greater than 200 vehicles/h, protected release of the traffic turning left using a four phase control system permits a greater number of oncoming vehicles than is the case if traffic turning left passes through the oncoming traffic unprotected.

Comparison of the control variants reveals the following basic findings:

- At volumes of up to approximately 120 vehicles turning left per hour, the fact that they flow away during the phase transition makes it possible for them to turn without a special phase, and thus without restricting the oncoming traffic.
- Even a small increase in the number of vehicles turning left (e.g. 200 vehicles turning left that hour) means that protected release using a four-phase control system provides clear benefits with respect to the oncoming traffic capacity.
- The maximum advantage provided by protected release lies in the region of 350 vehicles/h, where the volumes of oncoming traffic and traffic turning left are approximately balanced.
- From the perspective of capacity, it is better to provide for protected release of traffic turning left during a lagging green, provided that this is programmed to be variable on demand. This release time cannot, however, be extended without limit, because a minimum green time is reserved for oncoming through traffic, and there may also be traffic turning left in the opposite direction, which should also be granted a release time. For this reason, the curves for these volumes of traffic with a variable release time terminate in the middle of the range of traffic volumes.

This investigation only includes the stream of traffic turning left and the oncoming stream of through traffic. As a result of the triangular islands, oncoming traffic turning right is not considered. Figure 2 shows the effects of these programs on the overall capacity of the intersection under the same conditions. This indicates the total volume of traffic that a signal-controlled intersection can handle when certain proportions of this total volume are caused by traffic turning left and when different control systems are installed. In detail, Figure 2 indicates the following:

- The maximum total capacity of the intersection under investigation here is just under 7000 vehicles/h. This is achieved when two phases are used, the proportion of traffic

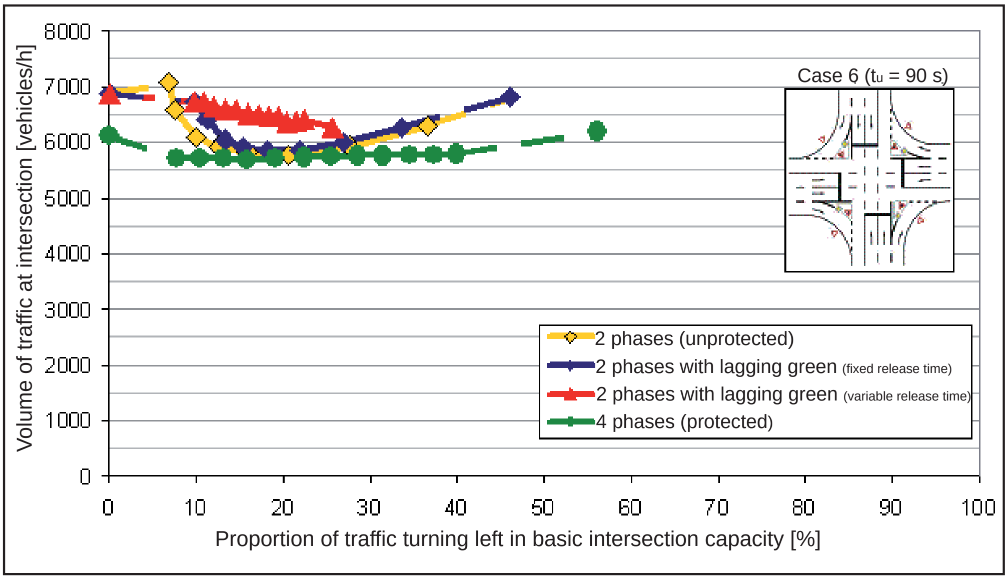

Figure 2:
Volume of traffic at an intersection using different control types for large intersections with triangular islands (case 6) with a cycle time of 90 s

turning left does not exceed 7 % and all the traffic turning left is able to flow away during the phase transition.

- In the case of protected release for the traffic turning left using a four-phase control system, the total capacity is reduced to a little more than 6000 vehicles/h as a result of the necessary transition times and the need to temporarily block traffic turning right alongside the triangular islands (a protected phase for traffic turning left may only be activated if no conflicting stream is released at the same time). Under certain circumstances, this reduction could be avoided if the triangular island is widened to such an extent that free traffic turning right no longer flows into the intersection with the need to yield, but is instead introduced into the through lane in a merge area.
- As the proportion of traffic turning left increases between 7 % up to approximately 18 %, the capacities supported by the different types of control approach each other and reach comparable values of approximately 5800 vehicles/h between 20 % and 25 %.
- If the proportion of traffic turning left continues to increase, a form of control with no protection for traffic turning left provides greater overall capacity, because traffic turning right can flow freely.
- The apparently high capacity provided by control methods with lagging green, above all if this is implemented at a variable duration, only applies on condition that the traffic turning right freely can flow away without being signal-controlled. However, for reasons of safety and capacity, this presupposes the geometrically complex solution already mentioned, in which merge lanes are used to allow this traffic turning right to merge into the main stream without difficulty.

To summarize, this means that the approximately 20 % increase in capacity of the intersection under these geometric conditions results from the fact that the opposing streams of traffic turning right must be blocked temporarily during protected release of the traffic turning left. This improvement only arises, however, if the proportion of traffic turning left forms significantly less than 10 % or 30 % or more of the overall volume of traffic. Under traffic volume conditions that occur frequently, the overall capacities only differ marginally.

2.6.2 Large intersection without triangular islands (case 4)

A large intersection without triangular islands and with a cycle time of 90 s was investigated in order to provide a comparison with case 6 (the corresponding geometry with triangular islands). This case was also calculated using a cycle time of 60 s. This also serves to provide a comparison with small intersections with only one lane per approach, that tend to be operated with short cycle times.

A cycle time of 90 s results in the situation shown in Figure 3 with respect to the volumes of traffic in the conflict area between traffic turning left and oncoming traffic. In this case, the oncoming traffic is made up of through traffic and traffic turning right.

In contrast to an intersection with triangular islands, the volume of oncoming traffic is just under 1600 vehicles/h, as two lanes are available. The difference in transition times results in a slight reduction below twice the volume of traffic from case 6.

From a qualitative perspective, the reductions in traffic volumes using different phase systems show a similar behaviour to that in case 6 (with triangular islands), but the quantitative effect is considerably greater:

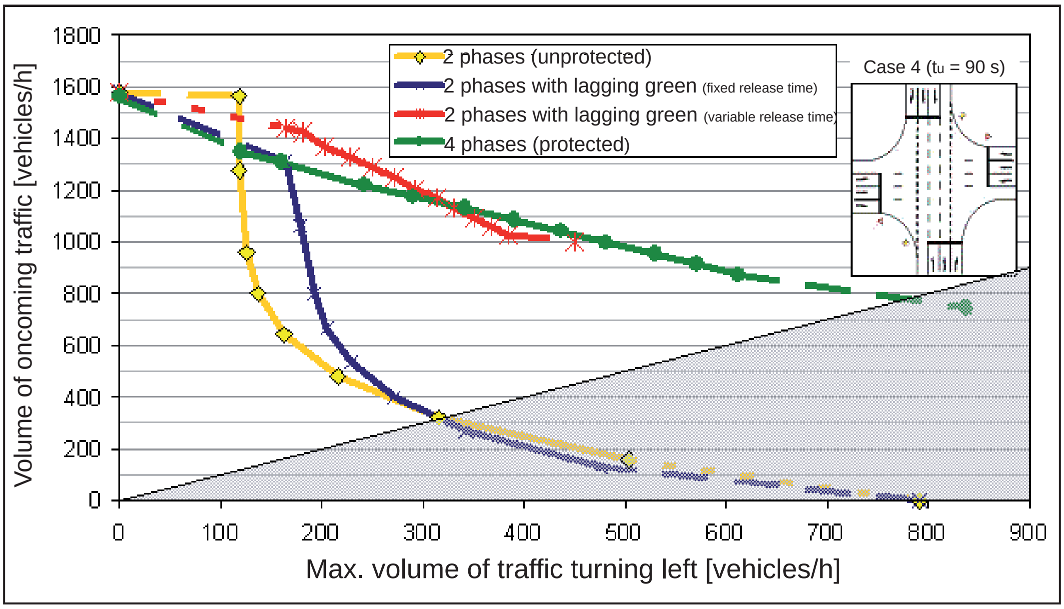

Figure 3:
Comparison of the influence of a conflicting vehicle turning left using different control methods for traffic turning left on the maximum volume of higher priority oncoming traffic for large intersections without triangular islands and a cycle time of 90 s.

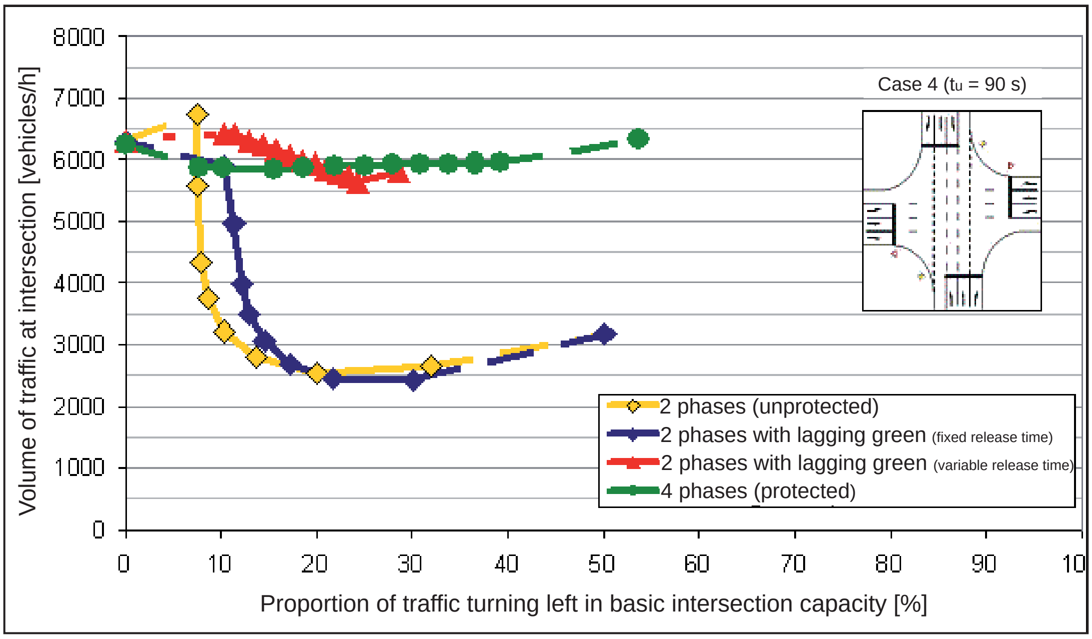

Figure 4:
Volume of traffic using different control types for large intersections without triangular islands (case 4) with a cycle time of 90 s

The reductions in capacity in the case of unprotected release are considerable, because the oncoming traffic occupies two lanes. This means that the probability of sufficiently large time gaps occurring to allow traffic turning left to pass through the oncoming traffic only arises to a sufficient extent when the volume of oncoming traffic is very small (less than 500 vehicles/h). Protected release using a four-phase system, on the other hand, makes it possible to handle between 800 and 1000 vehicles/h without difficulty when the volume of traffic turning left is high. This results from the fact that traffic turning right can be released simultaneously with traffic turning left originally traveling in a parallel direction.

The capacity of the entire intersection relative to the proportion of traffic turning left is shown in Figure 4. The following results can be seen in this figure:

- The maximum total volume of traffic is 6300 vehicles/h.
- The reduction in the overall capacity of the intersection in the case of unprotected traffic turning left is considerable.
- In the case of streams of traffic turning left protected by a four-phase control system, the overall capacity of the intersection remains at around 6000 vehicles/h, irrespective of the proportion of traffic turning left.

In cases where there is more than one lane of oncoming traffic, as investigated here, protected phase of traffic turning left is not only urgently needed for reasons of safety, but must also be recommended when considering capacity.

At a cycle time of 60 seconds, the overall capacity of the intersection is reduced slightly to 6000 vehicles/h. The capacity is lower as a result of the greater proportion of transition times.

2.6.3 Medium-sized geometrically symmetrical intersection (case 3)

The intersection under investigation here represents a relatively frequent case in which there are two lanes on each appoach. The right-hand lane is for through traffic and traffic turning right and the left-hand lane is for traffic turning left. Calculations were carried out with a cycle time of 90 s. Separate protection or release for traffic turning right is not possible because the lane is shared with through traffic, with the result that all oncoming traffic must be blocked if traffic turning left is protected when released.

Figure 5 shows the volumes of traffic in the conflict area between traffic turning left and oncoming traffic. We can see that with a low volume of traffic turning left, up to around 830 vehicles/h can flow away in the oncoming direction. The capacity for traffic turning left to flow away during the phase transition is exceeded at more than 120 vehicles turning left per hour, and further possibilities for traffic turning left are only available if large time gaps in the oncoming stream occur, so that it is necessary for the volume of oncoming traffic to drop considerably, e. g. to less than 400 vehicles/h. At these volumes, the capacity of oncoming traffic is regularly considerably more favorable when a four-phase control system or variable lagging green is used.

The overall capacity of the intersection in relation to the proportion of traffic turning left is shown in figure 6. This clearly shows the advantage of protected release in the case of larger proportions of traffic turning left in the overall capacity:

- With a proportion of up to 14 % of traffic turning left, the two-phase system provides significantly greater capacity than all other types of control. Nevertheless, when the proportion of traffic turning left is expected

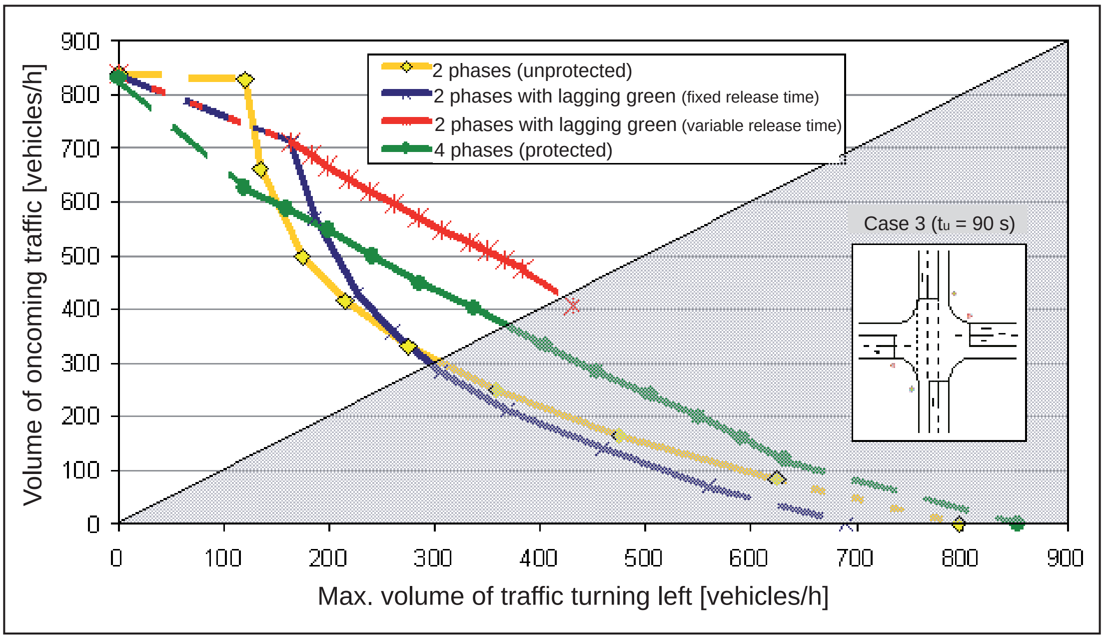

Figure 5:
Comparison of the influence of a conflicting vehicle turning left using different control methods for traffic turning left on the maximum volume of higher priority oncoming traffic for medium-sized intersections and a cycle time of 90 s.

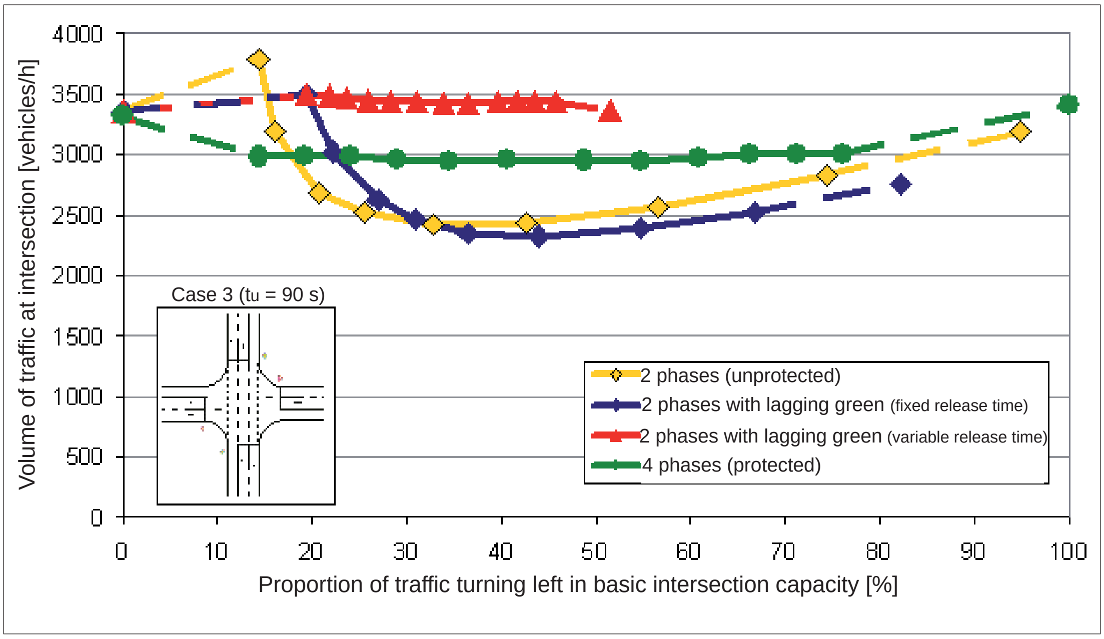

Figure 6:
Traffic volume at intersections using different types of control for medium-sized intersections and a cycle time of 90 s

to be between 20 % and 40 %, this type of control is particularly unfavourable.
- Protected release for traffic turning left (four-phase control) results in an overall capacity of approximately 3000 vehicles/h for the intersection (which corresponds approximately to half the capacity of multi-lane intersections in case 4).
- A control system with variable lagging green results in the highest capacities. The total capacity is approximately 3500 vehicles/h. This solution can, however, only be considered when the traffic volumes are asymmetric, as it can only be used for one direction.

Overall, therefore, we see that with larger volumes of traffic turning left, protected release always delivers better results than the two-phase system, even from the perspective of capacity. The proportion of traffic turning left is, however, somewhat higher than with multi-lane intersection approaches, as the volume of traffic in the through streams can reach considerably higher values. The absolute size of the critical streams of traffic turning left is approximately 500 vehicles/h across all approaches in both cases.

2.6.4 Small intersection with one lane on all approaches (case 1)

This geometry causes the lanes to be used as mixed lanes for all traffic stream types. The result of this is that the traffic behaves in a completely different manner from the cases studied previously, because traffic turning left cannot flow separately from the other streams of traffic and all other streams of traffic are also affected by traffic traveling in the same direction and turning left. The strategy previously used to simulate full capacity only delivers meaningful results to a certain extent, because the traffic turning left is not subject to any restrictions, and as a result the traffic streams develop with a virtually equal distribution without further constraints. For this reason, a second series of simulations was calculated in which the volume of traffic turning left was restricted to a maximum proportion of around 10 % of the overall volume of traffic on each approach.

The following applies at a volume of traffic turning left and oncoming traffic for both load cases (10 % and 33 %):
- If it is assumed that there is no traffic turning left, the maximum volume of traffic is 800 vehicles/direction.
- Even at low volumes of traffic turning left, the volume of oncoming traffic decreases considerably, irrespective of whether only two phases are used or lagging green of fixed or variable duration are also used.
- If the volume of traffic turning left is reduced while its proportion of the volume of traffic remains the same, the quantity of oncoming vehicles is also reduced. If more traffic turning left is permitted and the proportion is increased up to 33 %, the volume of oncoming traffic is necessarily also reduced.
- Protected release is only possible if each approach is individually released.

As far as the overall capacity of the intersection is concerned, this means that approximately 3200 vehicles/h can pass through the intersection if there is no traffic turning left. This value decreases considerably to values below two thirds of the original level even if there is only a small proportion of traffic turning left without any protected release or with a fixed or variable lagging green.

If each approach is individually released, 1200 vehicles/h can pass through the intersection. This represents fourfold the volume of traffic on the individual approaches. This value remains constant and is not influenced by the proportion of traffic turning left.

In summary, it can be said that in the case of such geometries, only very poor capacities can result when traffic turning left is taken into account. Every effort should therefore be made to at least provide left-turn lanes wherever possible on the individual approaches.

2.6.5 Combination of different approaches at an intersection

In real life, different approaches are very frequently combined with each other at intersections. In cases such as this, the relevant representation of traffic volumes in the conflict areas can be used to derive the maximum capacities that arise by combining the volumes in the traffic streams. Table 1 shows all theoretically possible combinations of the four different approaches that were investigated. Combinations which were investigated are highlighted in color. Other meaningful combinations are indicated.

This results in values which lie between the relevant overall conditions for uniform constructions. These combinations were derived by drawing analogies from the existing results without performing any additional simulations. This means that no new transition times were taken into consideration. The results show that the differences in capacity between protected and unprotected control systems are confirmed for medium to high volumes of streams of traffic turning left. Generally, the variant with protected control delivers considerable benefits for the overall capacity of the intersection. With the exception of small proportions of traffic turning left (up to 10 %), two-phase control in no cases delivered greater capacity.

2.6.6 Protected release of traffic turning left as leading green, lagging green or a combination of both, with fixed and variable durations for each

For reasons of traffic safety, the lagging green option is generally chosen if the release time is extended in favour of traffic turning left. In other words, when the release time for the oncoming traffic has ended, the oncoming traffic is stopped, and additional time (lagging green) is provided for traffic turning left. If the additional release time is provided before the oncoming traffic is released, this is referred to as leading green. The different effects of various leading green and lagging green variants were tested for case 3 and a cycle time of 90 s. This showed that:

- Leading green achieves somewhat higher capacities than lagging green.
- Regulation using leading green or lagging green is only possible in one direction of travel. The opposite direction must do without a separate release time for traffic turning left. This therefore only makes sense if the volumes of traffic are asymmetric.

Table 1:
Categorization of intersection types

Intersection type	Primary direction: Number of lanes – Left-turn	Through	Right-turn	Triangular islands	Secondary direction: Intersection type – Case 1	Case 3	Case 4	Case 6
Case 1	1			no	+	–	–	–
Case 3	1	1		no	+	+	–	–
Case 4	1	1	1	no	–	+	+	–
Case 6	1	1	1	yes	–	+	+	+

Note : Intersection types + sensible – not sensible; green: investigated; yellow: combined

- Provision for both directions of travel necessarily leads to a combination of leading green and lagging green. This permits a greater volume of traffic turning left at higher volumes of oncoming traffic. The fact that signal states are difficult to understand must, however, be taken into account.
- Variable leading times or lagging times can only be granted limited durations.

2.6.7 Effects of different cycle times

As a rule, shorter cycle times always cause the loss resulting from phase transitions to be proportionally greater, because the transition times must be assigned values of the same absolute duration. This means that the intersection capacity will generally rise as the cycle time rises. Capacity does not, however, increase linearly with the cycle time, because the time losses have a proportionally smaller impact with longer cycle times.

2.6.8 Possible volumes of traffic turning left when the volume of oncoming traffic is high

With all multi-lane variants of intersection approaches and low volumes of traffic turning left, it is the case that up to approximately 120 vehicles turning left/h can flow away during the phase transition (at a cycle time of 90 s), and that through traffic is therefore not restricted even in the event of unprotected release. Up to this volume of traffic, protected release will always result in reduced capacity for the oncoming traffic, because the time for the special phase must be taken away from the oncoming traffic. The greater the number of cycles per hour (i.e. shorter cycle times), the greater the number of vehicles turning left that can be accommodated during the phase transition. On the other hand, however, the number depends on the geometry of the intersection (number of spaces that the vehicles can occupy in the intersection).

The negative impact on capacity of the special phase for low volumes of traffic turning left is lower if lagging green is used. This is, however, only possible in one direction of travel (asymmetric solution).

As soon as more than 120 vehicles wish to turn left, protected release for these streams sometimes has considerably a higher capacity than the two-phase solution. Setting up a lagging green solution (assuming that the volumes of traffic involved are asymmetric) always achieves better results, which can be continued into the realm of higher volumes of traffic turning left by using variable release times. If high volumes of traffic turning left occur in both directions of travel, a four-phase control system must be selected in the majority of cases if leading green is to be avoided (because of the associated safety issues).

The maximum possible volume of traffic turning left in relation to the control method is shown for different geometrical configurations in Figure 7. The values shown there have been taken from the graphs and rounded to practical values. The volume of traffic per lane is assumed to be 600 vehicles/h (i.e. 1200 vehicles/h in the case of two lanes in the opposite direction). It can be seen that only marginally more vehicles can flow away in the event of two-phase control than can flow away during the phase transition. In the case of protected release, this value is sometimes considerably larger, i. e. in particular in cases with multiple lanes, a considerably higher volume of traffic turning left can be handled in the special phase by granting a greater proportion of time. Variable lagging green leads to the greatest number of vehicles turning left flowing away, but it can only be used for one direction of travel.

The small intersection with only one lane per approach is a special case: The findings here cannot be compared with those for the other intersections. In these cases, release in protected phases leads to a noticeable reduction of the overall capacity in the conflict area. 300 vehicles can pass this conflict area per hour (this is the capacity of a single-lane intersection approach if each approach is individually released. The greater the volume of traffic turning left, the lower the capacity for the remaining traffic.

2.6.9 Overall capacities of intersections with different types of control

The overall capacity at an intersection reaches approximately 3300 vehicles/h in the case of two-lane approaches and a little over 6000 vehicles in the case of three-lane approaches. If traffic turning right can flow away unhindered (alongside triangular islands that are not signal-controlled), this value increases to almost 7000 vehicles/h.

As soon as a significant number of vehicles turning left arises, the overall capacity of the intersection is reduced, particularly in the case of the unprotected release, at a 15 % proportion of traffic turning left (two-lane approaches) or 7 % proportion of traffic turning left (three-lane approaches). In contrast, multi-phase systems only show a slight reduction of the intersection capacity as the proportion of traffic turning left rises. Under favourable conditions, the overall capacity remains virtually constant. Protection of traffic turning left by means of lagging green, particularly if this can be made variable, sometimes results in considerably higher overall capacities than with four-phase control, at least up to the range of a 20 % proportion of traffic turning left.

Large intersections with traffic turning right freely (case 6) are also special cases: In such cases, only protection with lagging green delivers greater capacity compared with an unprotected two-phase system, whereas the multi-phase systems can only achieve a maximum of the same capacities for the mid-range of the proportion of traffic turning left. The reason for this is that unprotected two-phase systems allow traffic turning right to

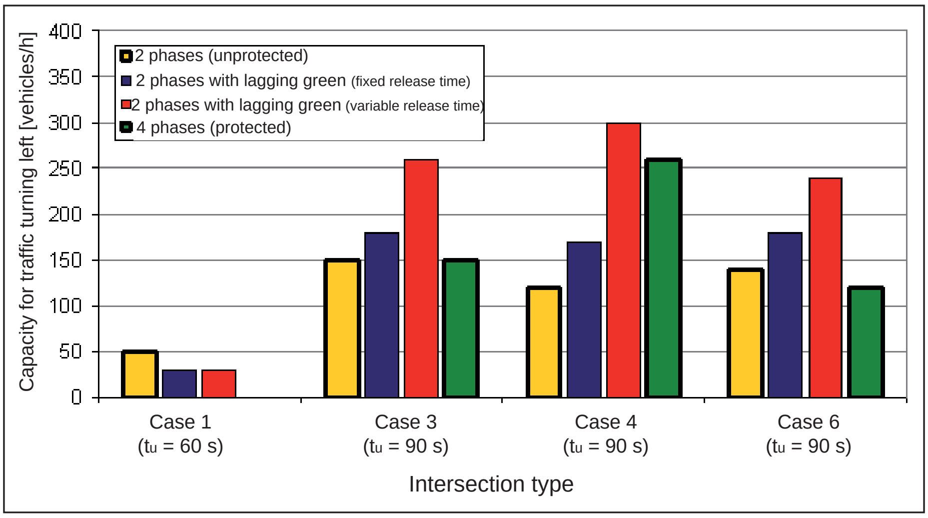

Figure 7:
Capacities for traffic turning left at a volume of oncoming traffic of 600 vehicles/(h*lanes) for different control variants for traffic turning left and different intersection types – results of the simulation runs

constantly flow freely. This means that this effect only occurs when there are high volumes of traffic turning right. Turning this conclusion around, a large proportion of traffic turning left would also arise, with the result that the values for a low volume of traffic turning left will not be realistic.

3 Recommendations

The greater level of safety provided by multi-phase systems means that unprotected two-phase systems should in principle no longer be used. Traffic-related reasons mean that in isolated circumstances capacity may be restricted as a result of the additional protection for traffic turning left. The following recommendations for deployment are made:

(1) With high volumes of traffic, e. g. in the case of traffic volumes greater than 6500 vehicles crossing an intersection per hour, it is necessary to create multiple lanes for individual traffic streams. In this case, unprotected release of traffic turning left should never be considered because it is not possible to ensure safety.

(2) If the volume of traffic is between 4000 and 6500 vehicles/h, three-lane intersection approaches are generally necessary from all directions. Assuming a uniform distribution of traffic relations, the average proportion of traffic turning left is 25 %.

- If traffic turning right is directed alongside triangular islands and flows freely at times, a four-phase control system achieves the same capacity values as two-phase control systems. Protecting traffic turning left by means of lagging green is in most cases not viable, as it requires the volume of traffic turning left to be concentrated on a maximum of two of the four directions of travel (asymmetric volumes of traffic). For reasons of safety, the possibility of traffic turning left passing through the oncoming traffic should not be allowed.
- In the case of three-lane approaches without triangular islands, a four-phase control system is by far the most favorable solution if the volume of traffic on the intersection is uniformly distributed both from the perspective of traffic flow and from the perspective of safety.

(3) In the case of overall volumes of traffic of 3000 to 4600 vehicles at peak hours, mixed geometric types of intersection will occur. For instance, in the primary direction, the lanes will be divided in a similar way to case 4 (three lanes without triangular islands) and in the secondary direction, two-lane approaches will be used as in case 3. If the volume of traffic is distributed uniformly i.e. if the proportion of traffic turning left is around 25 % of the overall capacity, a four-phase control system will also provide ideal traffic conditions in such cases. Lagging green may also be considered as an option here, provided that the situation can be avoided where traffic turning left passes through the two lanes of oncoming traffic.

(4) In the case of traffic volumes between 2000 and 3000 vehicles in peak hours, lagging green should be considered if the proportion of traffic turning left is below 20 %. If the proportion of traffic turning left is greater, a four-phase control system will always be advantageous.

(5) Single-lane approaches should never be planned for traffic volumes between 1000 and 3000 vehicles at peak hours. Only a two-phase system of traffic light control would deliver sufficient capacity. Establishing a lane for traffic turning left must be called for in such circumstances (and can also be justified economically).

(6) At capacities of up to 1200 vehicles at peak hours, single-lane approaches with protected release of traffic turning left can be established. It is recommended that these are used up to approximately 1000 vehicles/h.

4 Conclusion

The results of the study by the Technische Universität Dresden can be summarized as follows:

- In the case of large intersections with a high volume of traffic, a separate signal for traffic turning left must always be provided. This considerably increases safety for traffic turning left, oncoming vehicles, pedestrians and cyclists.
- In the case of large intersections with a medium volume of traffic and small intersections with a high volume of traffic, “protected” systems for traffic turning left are the most efficient solution both in terms of traffic flow and traffic safety.
- Solutions with no separate signal for traffic turning left can only be justified at small intersections where there is no lane for traffic turning left and where the volume of traffic is low.
- It may be necessary to completely prohibit traffic from turning left.
- The costs for converting the traffic signal system to a separate phase for traffic turning left generally lie considerably below the accident costs that can be avoided.

On the basis of the research findings, German Insurers Accident Research (UDV) calls for the following:

Newly installed traffic signal systems must always have a separate green phase for traffic turning left at intersections; existing systems must be converted without delay if there are known problems; all other systems must be converted at the latest when construction measures are due anyway.

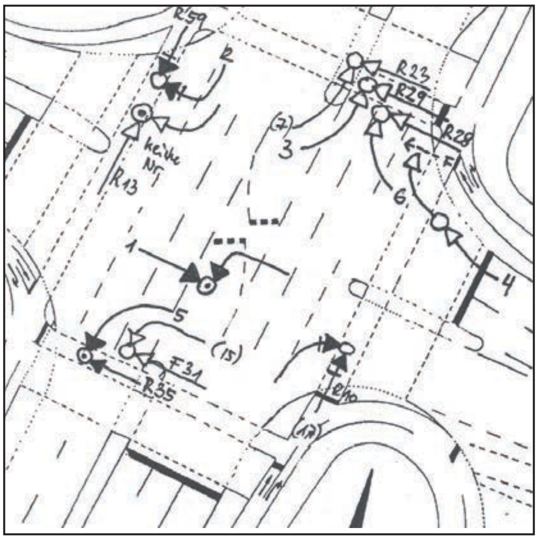

Figure 8: Example showing an accumulation of accidents resulting from the lack of a phase for traffic turning left (traffic turning left and cyclists and pedestrians also released in parallel)

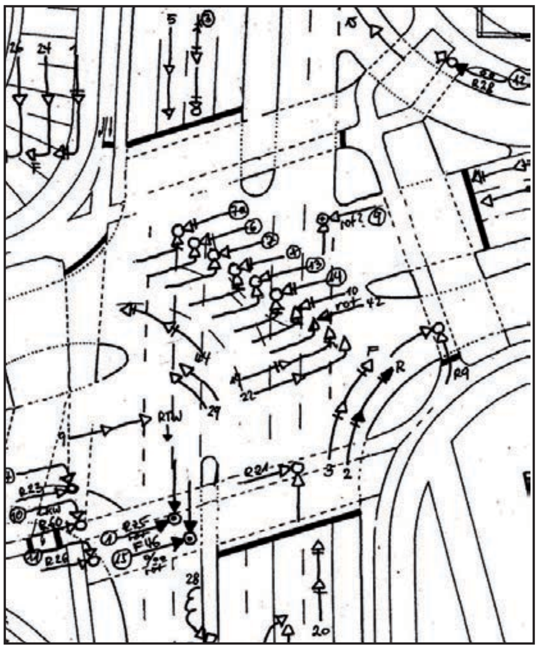

Figure 9:
Example showing an accumulation of accidents resulting from the lack of a phase for traffic turning left (traffic turning left with oncoming traffic)

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