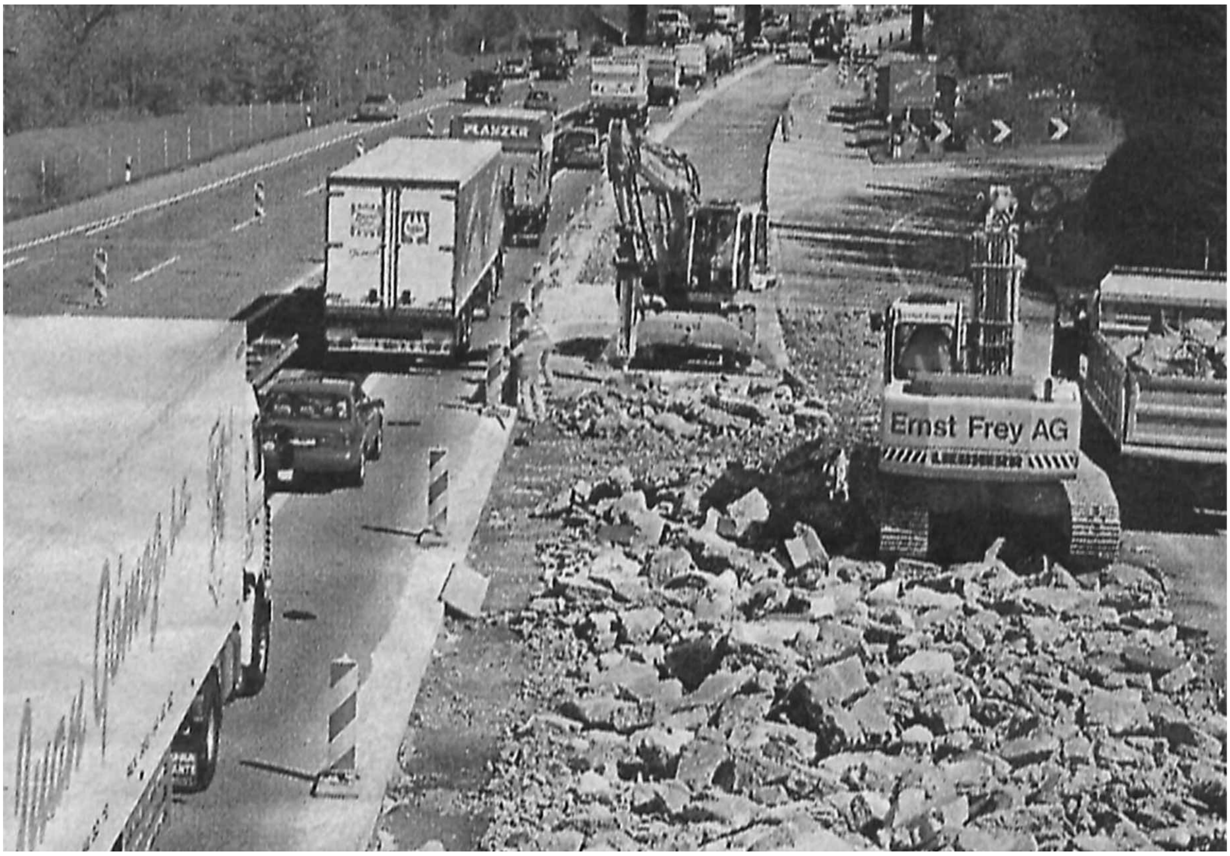

Traffic flow and accident occurrence in construction zones on freeways

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Abstract

This paper concentrates on the issue of layout/design and the resulting effects on the driver behavior of vehicles in the transition area ahead of construction zones. This involved investigating various trial layouts. The data collections were deliberately scheduled for periods of low to medium traffic volumes.

Accident occurrence

In order to assess traffic safety, accident occurrence at six previous construction zones on Swiss freeways was investigated, along with findings from accident investigations at construction zones on foreign freeways. For the four stretches of freeway selected for the research project, the following parameters were evaluated and analyzed with reference to the before/after and with/without comparisons: accident location (i.e. which construction zone) and direction of travel or carriageway; type of accident (how the collision occurred), parties involved in accident (types of vehicle) and accident consequences (enumeration of the injuries and damage to property caused).

Field trials

In the field trials at construction zones on freeways, the effects on driver behavior were investigated with various posted speed limits and with various channelization devices ahead of respectively in the approach area to the construction zone. Data was collected at four selected stretches of freeways with construction zones, using a total of 16 trial layouts. Speed behavior and lane changes in the approach areas to the construction zones were measured, along with track behavior in the crossovers. Data relating to a total of 32’630 vehicles was collected at the measurement cross-sections in the four constructions zones.

Analyses of the measurement results

The following descriptive quantities were used in assessing the results of the measurements:

- For the speed distribution at the representative cross-sections: the standard deviation S at the average speed V_a and
- for the speed adjustment: the speed differences and the average decelerations between the relevant cross-sections. The vehicle groups used were those of “all veh.” (denoted by V_a) and “fast-moving veh.” (denoted by $V_{85\%}$).

- Similarly, for the track distribution: the standard deviation at the relevant cross-sections and

- the deviation in the average position of the vehicle axis from the center of the traffic lane.

- For lane changes: the frequency and direction of the lane changes in the approach area in front of the construction zone.

In analyzing the effects, the first step was to check which of the changes are statistically significant in the comparison of the different trials. The second step was to look for possible explanations for the significant changes regarding safety by influences inherent in, and/or independent of, the different trials.

Recommendations

Based on these findings, recommendations were made for the design of freeway construction zones. They apply to construction-zone operating forms which do not entail reducing the number of lanes.

The conclusions can be laid out as follows:

- Signposting: speed limit at construction zone
- Signposting: location of the speed signs
- Traffic monitoring
- Channelizing devices
- Further measures

Keywords

construction zones on freeways – driving behaviour – channelizing device – transition area – accident occurrence – traffic flow – STRC 2006 – Swiss Transport Research Conference

1. Background

Previous research into construction zones on freeways has indicated that the main problems concerning traffic safety are located in the transition area between the open freeway and the construction zone. This includes the upstream section of the freeway with a suitably reduced speed limit as well as the transition or approach area. Traffic flow along the influence of the construction zone is generally uniform, but in the approach area, as speeds are adjusted to the posted speed limit, inconsistencies arise. This is manifested in the form of greater speed variation and more frequent lane changes.

The aim is to appraise the effects on traffic flow and thus on traffic safety. Principles and recommendations are to be worked out for locally expedient arrangements in the transition area ahead of construction zones with various operating forms.

2. Research aim

The research project has the following aims:

- Identifying the fundamental correlations between the structural/operational elements which characterize the transition area ahead of the construction zone and the characteristics of the traffic flow at different types of construction zone. For this aim empirical trials are deemed necessary.

- If the indicated correlations can be quantified, an estimate of the consequences of the most important elements/element groups on the traffic flow and the safety shall be carried out.

- Principles and recommendations for the expedient arrangement of the approach area at the different types of construction zones on freeways shall be derived. References to customizations or completions of existing standards have to be aimed at. The standard itself is not part of the research.

A comprehensive evaluation of previous internal and foreign knowledge of traffic and accident occurrence at construction zones is necessary for accomplishing the aims mentioned above. That for both, research results and experiences from earlier construction sites have to be included.

3. Previous research

3.1 Knowledge from Switzerland

Only few research was carried out on the topic "traffic flow and safety in construction zones on freeways" in Switzerland till now. These can be dated to the time at 1990 and deal primarily with questions of efficiency. Experiences with the traffic and accident events at single construction zones which were established in Switzerland and often operated successfully, are more informative and therefore included in the considerations.

That for larger construction sites could be included from the cantons of Zurich, Lucerne and Argovia. Accident data was evaluated from the time periods with and without construction work. The construction sites were established during several months within the year range 1998 to 2000. During the construction work the operating forms have changed.

3.2 Foreign knowledge

With regard to own examinations, several research and experience reports from Germany and Austria were also sighted. The results of the literature evaluation are summarized briefly in the research report [1].

4. Measurements

With the field trials at construction sites on freeways the effects on the traffic and speed behaviour shall be examined at different signalled speed limits and for different channelizing devices in front of and in the introduction area of the construction site. This was inquired with at least 16 different trial layouts in the area of four construction sites.

4.1 Influencing variables

With the field trials the driving behaviour shall be evaluated during the different experimental setups. In the approach area the speed behaviour is of special interest. Moreover, the trace was of interest in the transition or displacement area of the lanes when driving on the introduction bend. The third group studied covered the events at lane changes.

4.2 Examination stretches

For the field trials, sections with mostly unhindered driving behaviour were chosen. So the traffic loads during measurement should not lead to disturbances or to jam formation.

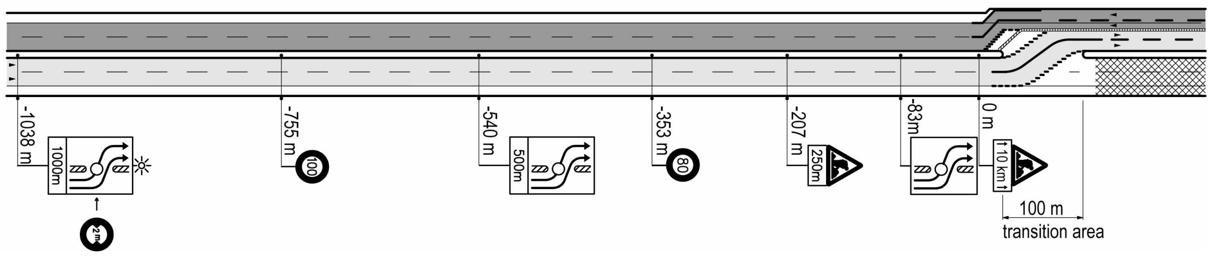
Decisive for the choice were:

- Typical, frequently used operating forms
- Traffic routing with transition area and without lane drop
- Traffic loads according to a DTV of approx. 40 000 –50 000 veh./day
- Readiness of the responsible persons to arrange the experimental setups
- Relative proximity to the domicile of the research institute.

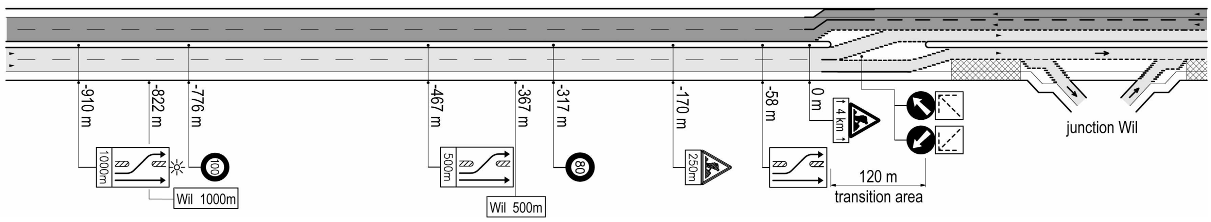
Due to these criteria, four construction sites were fixed for the examination, represented briefly in the following figure. The representations of the traffic routing are not to scale.

Figure 1 Examination stretches

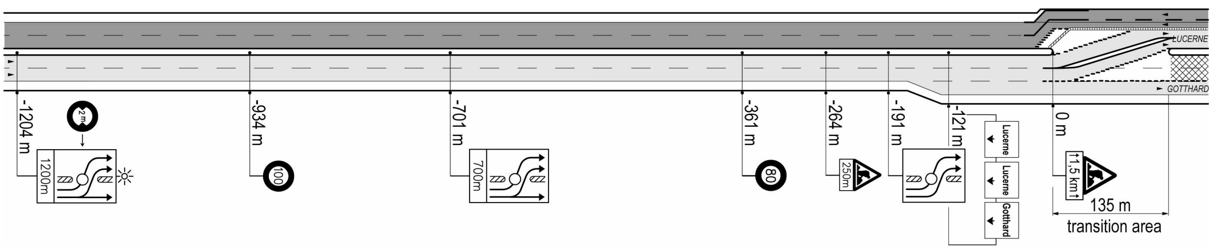
Saint Gall (SG1):



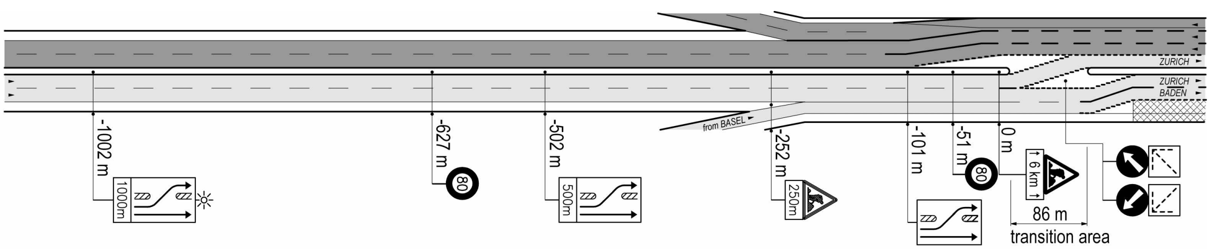
Saint Gall (SG2):



Zug (ZG1):



Argovia (AG1):



4.3 Trial layouts

The 16 trials as well as the accompanying day times of the data acquisition are arranged in the following table. The intended measuring duration of two hours could not be adhered at some tests for different reasons (e.g. delays in test rearrangement). The table is structured in:

- the order of the speed limit at the last sign in front of the transition area,
- the type, characteristics and possible combination of the used channalizing devices in and in front of the transition area and
- the additional elements (e.g. speed supervision with radar).

Measurements were carried out on the examination stretch SG2 at two different experimental setups (marker buoys/channelizing rails) both during the day and at night. All tests were carried out at favourable weather conditions during the summer months (June till September).

Table 1 Trial layouts

construction zone	operating form	used trial elements			additional trials	trial name	time of day
		speed limit (km/h)	channelizing device	additional elements			
SG1	4 / 0	80	marker buoys infront of barrier			SG1 1a	09.00 - 10.00
		80	marker buoys infront of barrier	radar monitoring		SG1 1b	08.30 - 10.30
		100	marker buoys infront of barrier			SG1 2a	13.45 - 15.45
		100	marker buoys infront of barrier	radar monitoring		SG1 2b	13.30 - 15.30
SG2	3 / 1	80	marker buoys	flasching arrows in high position		SG2 1a	08.45 - 10.45
		80	channelizing rail			SG2 1b	08.45 - 10.45
		80	marker buoys		at night	SG2 3a	21.45 - 23.45
		80	channelizing rail		at night	SG2 3b	21.50 - 23.50
		100	marker buoys			SG2 2a	13.30 - 15.30
		100	channelizing rail			SG2 2b	13.45 - 15.45
ZG1	4 / 0	80	marker buoys with flashing lights			ZG1 1a	10.50 - 12.50
		80	channelizing rail			ZG1 1b	13.00 - 15.00
		80	marker buoys with flashing lights	construction side portal		ZG1 2a	14.20 - 15.10
		80	channelizing rail			ZG1 2b	08.30 - 10.30
AG1	4 / 2 resp. 4 / 1	80	marker buoys / barrier	flasching arrows in high position		AG1 1	11.00 - 12.40
		100	marker buoys / barrier			AG1 2	13.30 - 14.10

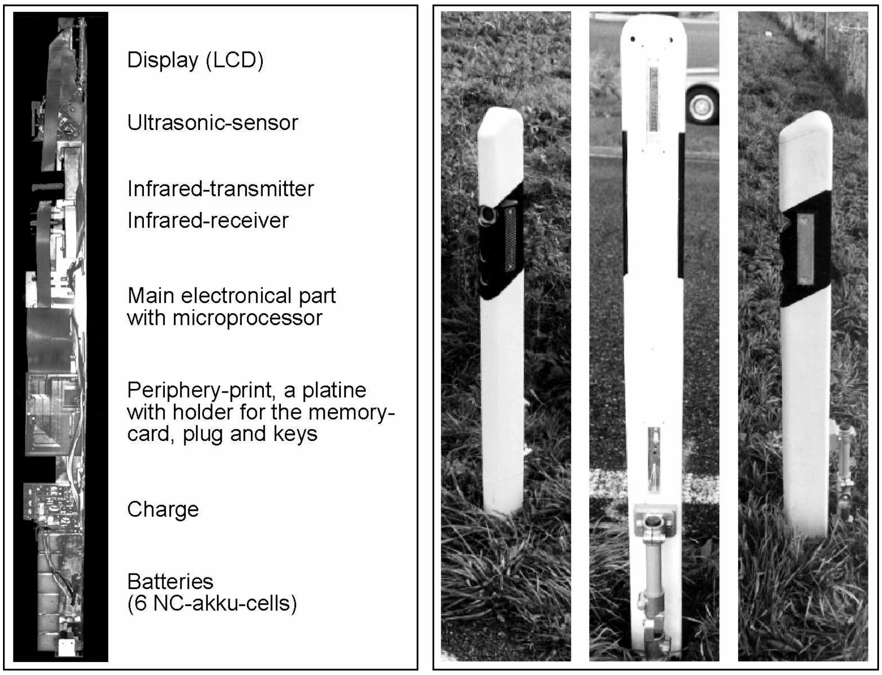
4.3.1 Measuring system

Inductive loops which were arranged along 900 to 1000 m formed the first measuring cross-section. They were installed between the first construction site signal and the first speed signal.

In general, four measuring cross-sections spaced with approx. 200 m were formed by inductive measuring plates placed in the middle of the lane. With these pltaes the traffic flow was followed up.

Measuring poles were used in the field trials as well. This equipment consists of autonomous measuring poles, disguised as regular delineator poles (see figure 2). The individual measuring pole, configured by a special control unit, can detect the pass-trough of the vehicles, their driving direction, the vehicle length and the lateral distance between the vehicle and the pole.

Figure 2 Views of the measuring pole

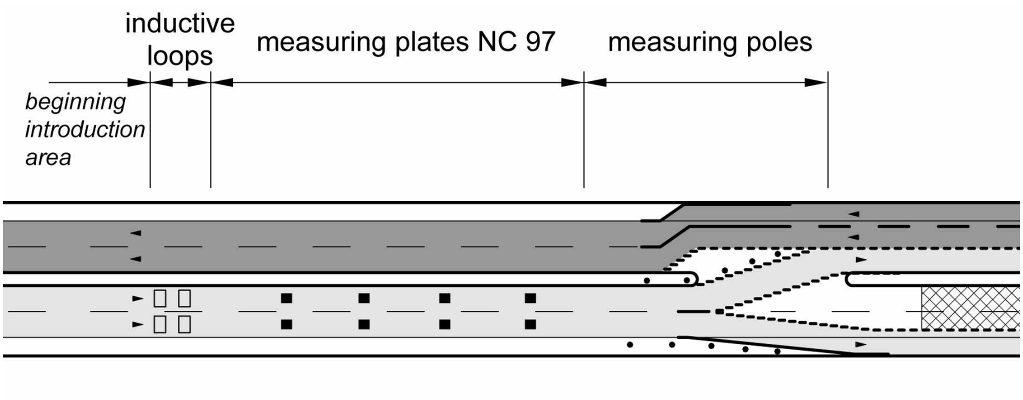


The speed of the vehicle is determined by analyzing the measured pass-through times in relation to the distances between the measuring poles. Each pole stores the collected data on memory cards, which are subsequently exported to a computer for further analysis.

Measuring poles were used along the transition area of the construction site. The theoretical speed cross-sections are defined between two poles each. The first pair of measuring poles marked the place were the introduction arch of the crossing of the separating strips or the displacement of lanes begun. The measuring poles were generally positioned in distances of 20 m. Obviously they were placed denser than upstream. This was necessary also with regard to the recording of the track behaviour of the vehicles. The exact sequence of the measuring posts at the individual examination stretches depends on the local geometry.

The generic layout of the measuring system is shown in figure 3.

Figure 3 Measuring system layout



5. Results

A short summary of the results of the accident examinations is given as follows. Also see the brief account of M. Laube presented at the 1st STRC in 2001 [2].

5.1 Accident occurrence

The accident evaluation of the four examination stretches has shown that when comparing the states during the construction work against the state without works, only one of the stretches shows a higher number of accidents and injuries/casualties (SG2). On all other examination stretches the number of accidents and injuries/casualties were equal or less.

Only at one examination stretch (ZG1) the comparison shows no change. At all other examination stretches with construction zones more accidents than on the respective comparison stretches have happened.

Due to the results, the thesis whereupon the freeway sections with construction zones show an increased danger standard can not be confirmed. This is also supported by the low number of accidents and injuries/casualties: 0.11 accidents/10^6 * veh * km and 8.8 injuries/casualties/10^8 * veh * km result as a mean average value from all four examination stretches.

Independently of the operation form, outstandingly many accidents occurred inside the construction zones. A distinct number of accidents happened on the smallest lane at the construction site SG1. The left lane measured only 2.50 m (permitted minimum according to the Swiss standard) and the right lane was 3.00 m wide at this construction zone. At all other examination stretch the lanes were over 0.50 m wider than in this special case.

5.2 Traffic flow

In this chapter, the results of the examination stretch SG1 are described exemplarily for all examination stretches. The results are structured into the three examination areas:

- speed behaviour ← whole section,
- track behaviour ← transition area,
- lane changes ← upstream section.

Concerning speed behaviour, progressions and their distribution are of main interest:

- Has an improved homogeneity of the speeds arisen in the context of a certain test trial layout?
- Is there a dependency between a particular trial layout and speed progressions with an improved (more punctual) adaptation to the construction site?

The first question can be answered by looking at speed distribution at every separate cross-section. To answer the second question the measured velocities at single cross-sections have to be compared to receive the data of acceleration.

Regarding track behaviour, the lane keeping (standard deviation around the middle position of the vehicle axes) and the distances to the lane demarcations are in the foreground. The distance to the middle position points out how far the trace courses differ from the ideal course along the lane axis (e.g.: "cut the corner").

In a first step it was checked whether there are differences in the trace distribution because of the descendant effect between unhindered vehicles (with time gaps to the vehicle driving in front, $\Delta t > 4$ s) and all vehicles (all Δt). The comparison of the standard deviations yielded a regression with high stability index. Due to this result the valuation of the trace behaviour is done at the basis of the group "all vehicles", moreover it means the greater size of sample.

The frequency of lane changes in the approach area of the construction site was evaluated. In addition to this the brake lights were distinguished, whether in connection with a change process, braking actions have appeared at one or more involved vehicles. The accumulation of these events can be interpreted as evidence of potential danger. These evaluations were possible only at those examination stretches at which the video recording shows the vehicle tails (SG1 and SG2). At the two other examination stretches (video recordings from the front) only the frequency of the lane changes could be determined.

5.2.1 Measurement results of SG1

Altogether four experiments were carried out on this examination stretch with the operating form 4+0. While the channelizing devices remained static, the speed limit was varied and the consequences of the speed supervision were examined. The trial SG1 1a formed the reference condition.

5.2.2 Speed behaviour

The number of evaluated vehicles is also indicated in certain tables (opening "all veh"). This detail refers to the respective test duration. It has to be taken into account that the duration at the trial SG1 1a was merely an hour while the other three tests lasted for two hours each. The hourly traffic was approximately the same in all tests.

5.2.2.1 Speed distribution

The changes of the speed distribution get examined at the single cross-sections (cs) in the range of the examination stretch. They get characterized by the standard deviation S which shows the variance of the measurements. So the consequences of the signalled maximum speed (speed limit 80/100 km/h) and the speed supervision (without/with radar) can be checked.

Influence of the speed limit:

The following tables show a comparison of the results at speed limit 100 and 80 km/h. The standard deviations (S) are arranged in table 2 for the trial without supervision (without radar) and the one in table 3 for the trials with supervision (with radar). The average values of S are respectively indicated for certain track sections in the right part of the tables. The column "1/2" includes the average values for the beginning of the approach area, the column "4/5" the one for the end of the approach area and the column "6/7/8" the one for the beginning of the transition area. The upper part of the tables shows the results for the right lane (rl), the lower part the one for the left lane (ll).

Table 2 Comparison of the standard deviations without radar monitoring

standard deviation S [km/h] **without radar monitoring** *(SG1 1a and 2a)*										all veh.		mean values		
speed	cs	1	2	3	4	5	6	7	8	%HGV	#veh	1/2	4/5	6/7/8
100	rl	16.4	14.7	12.9	13.8	13.2	10.7	10.4	10.3	26.8	1404	15.5	13.5	10.5
80	rl	17.5	15.6	13.6	12.6	12.3	8.4	8.5	9.2	23.6	678	16.5	12.5	8.7
	∆S	-1.1	-0.9	-0.7	1.2	0.9	2.3	1.9	1.1			-1.0	1.1	1.8
100	ll	11.6	10.9	10.2	9.6	9.2	8.8	9.0	8.7	2.1	1010	11.3	9.4	8.8
80	ll	12.9	11.6	10.2	10.8	9.4	7.5	7.8	8.7	2.4	425	12.2	10.1	8.0
	∆S	-1.3	-0.7	0.0	-1.2	-0.2	1.3	1.2	0.0			-1.0	-0.7	0.8

Table 3 shows the same comparison as table 2, this time with the influence of the speed supervision.

Table 3 Comparison of the standard deviations with radar monitoring

standard deviation S [km/h] **with radar monitoring** *(SG1 1b and 2b)*										all veh.		mean values		
speed	cs	1	2	3	4	5	6	7	8	%HGV	#veh	1/2	4/5	6/7/8
100	rl	16.4	12.8	11.0	11.8	10.8	9.6	9.2	10.6	23.9	1378	14.6	11.3	9.8
80	rl	15.9	12.2	10.4	10.6	9.6	8.2	7.5	7.4	21.9	1448	14.1	10.1	7.7
	∆S	0.5	0.6	0.6	1.2	1.2	1.4	1.7	3.2			0.5	1.2	2.1
100	ll	11.7	10.6	9.5	9.2	9.6	7.3	7.6	7.4	1.9	857	11.2	9.4	7.4
80	ll	11.7	11.1	10.4	9.1	8.1	6.2	6.4	6.4	2.4	872	11.4	8.6	6.3
	∆S	0.0	-0.5	-0.9	0.1	1.5	1.1	1.2	1.0			-0.2	0.8	1.1

Influence of the speed supervision:

The influence of the radar supervision is examined separately for the two signalled speed limits (80/100). Table 4 shows the results at speed limit 80 km/h, table 5, at speed limit 100 km/h. Of importance is that the radar cab (built visibly) was located at the measuring cross-section cs5 and signposted at cs2.

Table 4 Comparison of the standard deviations at speed limit 80 km/h

standard deviation S [km/h] **speed limit 80 km/h** *(SG1 1a and 1b)*										all veh.		mean values		
radar	cs	1	2	3	4	5	6	7	8	%HGV	#veh	1/2	4/5	6/7/8
without	rl	17.5	15.6	13.6	12.6	12.3	8.4	8.5	9.2	23.6	678	16.5	12.5	8.7
with	rl	15.9	12.2	10.4	10.6	9.6	8.2	7.5	7.4	21.9	1448	14.1	10.1	7.7
	ΔS	1.6	3.4	3.2	2.0	2.7	0.2	1.0	1.8			2.5	2.4	1.0
without	ll	12.9	11.6	10.2	10.8	9.4	7.5	7.8	8.7	2.4	425	12.2	10.1	8.0
with	ll	11.7	11.1	10.4	9.1	8.1	6.2	6.4	6.4	2.4	872	11.4	8.6	6.3
	ΔS	1.2	0.5	-0.2	1.7	1.3	1.3	1.4	2.3			0.9	1.5	1.7

The results at signalled speed limit of 100 km/h are arranged in table 5.

Table 5 Comparison of the standard deviations at speed limit 100 km/h

standard deviation S [km/h] **speed limit 100 km/h** *(SG1 2a and 2b)*										all veh.		mean values		
radar	cs	1	2	3	4	5	6	7	8	%HGV	#veh	1/2	4/5	6/7/8
without	rl	16.4	14.7	12.9	13.8	13.2	10.7	10.4	10.3	26.8	1404	15.5	13.5	10.5
with	rl	16.4	12.8	11.0	11.8	10.8	9.6	9.2	10.6	23.9	1378	14.6	11.3	9.8
	ΔS	0.0	1.9	1.9	2.0	2.4	1.1	1.2	-0.3			0.9	2.2	0.7
without	ll	11.6	10.9	10.2	9.6	9.2	8.8	9.0	8.7	2.1	1010	11.3	9.4	8.8
with	ll	11.7	10.6	9.5	9.2	9.6	7.3	7.6	7.4	1.9	857	11.2	9.4	7.4
	ΔS	-0.1	0.3	0.7	0.4	-0.4	1.5	1.4	1.3			0.1	0.0	1.4

It is summarizing to notice that the change of the speed limit (80/100) yields none or only insignificant effects on the local speed distribution. The influence of the radar supervision reduces the speed distribution. This primarily works at a lower speed limit, on the right lane and in the approach area ahead of the construction site. All results are influenced by the special situation of the examination stretch (upgrade).

5.2.2.2 Speed course

The changes in the speed progression at the examination stretch are examined due to the speed differences between selected cross-sections and the mean accelerations resulting from them. This allows to check the consequences of the signalled maximum speed (speed limit 80/100 km/h) and the speed supervision (without/with radar).

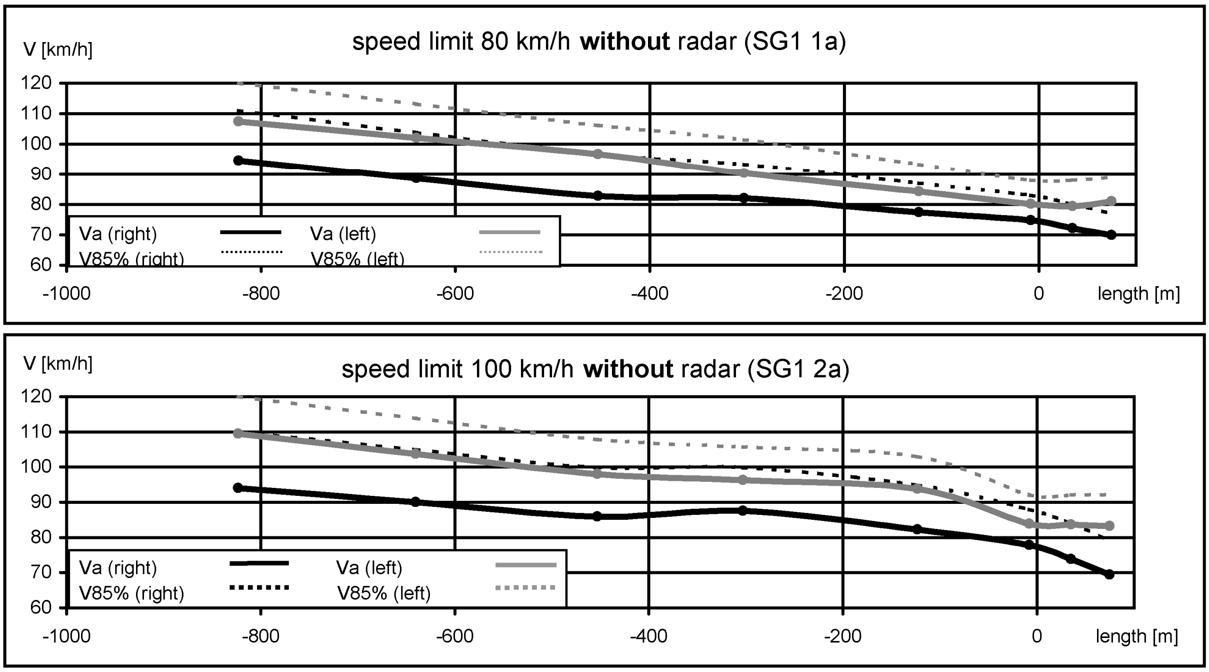
For the speed progression the unusual feature of the relatively large gradient of 5% on the examination stretch SG1 must be taken into account.

Based on the average speeds (V_a) the influences of the speed limit and the radar supervision are examined in the below. The third section ($V_{85\,\%}$) is about the influence of the fast vehicles.

Influence of the speed limit:

Figure 4 shows the speed progression of all vehicles in the condition without radar supervision at signalled speed limit of 80 km/h (above) and 100 km/h (below). The V_a and the $V_{85\,\%}$ are respectively represented for the right lane (rl) and the left lane (ll). The dots mark the positions of the measuring cross-sections (cs).

Figure 4 Speed progression without radar supervision, 80 km/h (above) and 100 km/h (below)



The progressions show a steady deceleration on the first approx. 400 m. At speed limit 80 km/h this progression continues up to the transition area. At speed limit 100 km/h the deceleration fades and reinstates shortly before the transition area. In the approach area on the left lane, V_a is approx. 15 km/h higher than on the right lane. The average speed difference goes down to approx. 5 km/h in front of and in the transition area. At the beginning of the approach area the $V_{85\,\%}$ is approx. 15-20 km/h (rl) or approx. 10 km/h (ll) higher than the average velocity (V_a). These differences are smaller in the second half of the approach area and in the transition area.

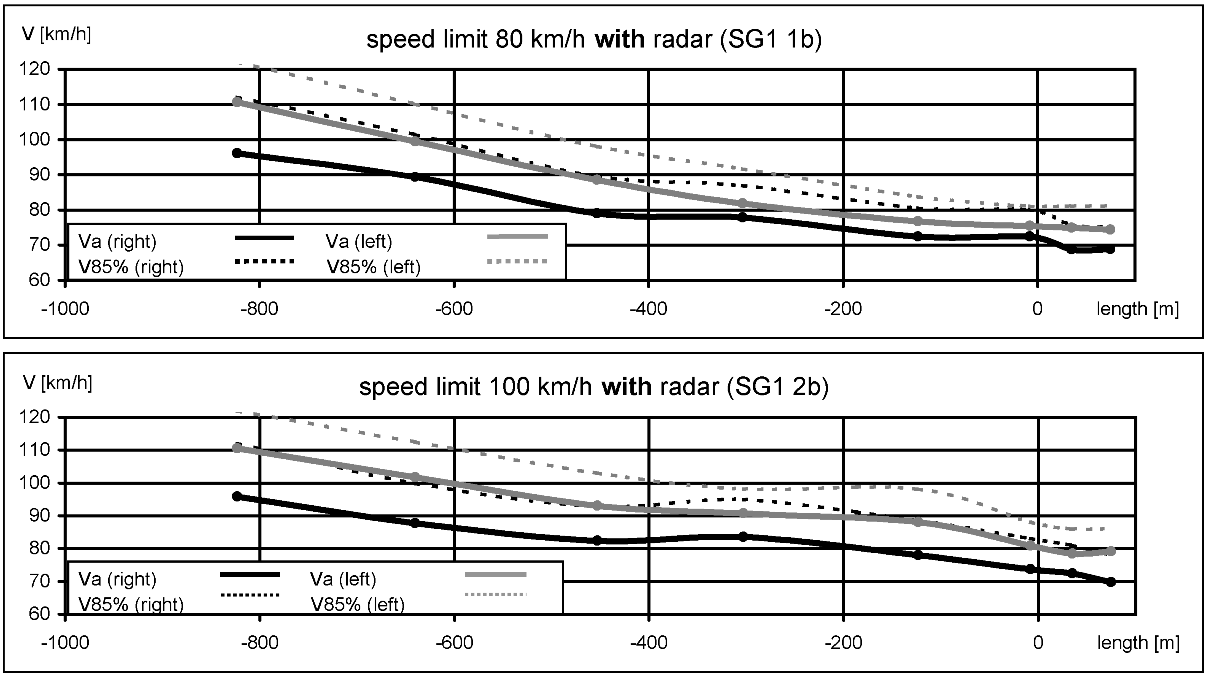
The consequences of the speed limit in the trial setup without radar supervision are shown in table 6. The structure of the table corresponds to the tables 2 to 4, in the right columns the speed differences between selected cross-sections ($\Delta V_{N/N}$) and the corresponding average values of acceleration (-) and deceleration (+) are indicated for the areas "approach" and "transition".

Table 6 Comparison of the average velocities at speed limit 100 km/h and 80 km/h without radar monitoring

V_a [km/h], ΔV [km/h] and a_a [m/s^2] **without radar** *(SG1 1a and 2a)*										approach		transition	
speed	cs	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	$\Delta V_{1/5}$	a_a	$\Delta V_{6/8}$	a_a
100	rl	94.0	90.0	85.9	87.5	82.2	77.8	73.8	69.4	11.8	0.11	8.4	0.57
80	rl	94.5	88.6	82.7	82.0	77.3	74.7	72.1	69.8	17.2	0.16	4.9	0.33
	ΔV	-0.5	1.4	3.2	5.5	4.9	3.1	1.7	-0.4				
100	ll	109.4	103.7	98.0	96.3	93.8	83.9	83.6	83.2	15.6	0.17	0.7	0.05
80	ll	107.4	102.1	96.7	90.3	84.2	80.1	79.3	81.0	23.2	0.24	-0.9	-0.07
	ΔV	2.0	1.7	1.3	6.0	9.6	3.8	4.3	2.2				

Figure 5 shows the speed progressions of all vehicles at signalled speed limit of 80 km/h (above) and 100 km/h (below) with radar supervision.

Figure 5 Speed progression with radar supervision, 80 km/h (above) and 100 km/h (below)



In the trial setup with radar supervision a more distinctive speed decrease in the first half of the approach area can be mentioned than in the setup without radar supervision (cf. fig. 4). In the further progression of the examination stretch this trend disappears. At speed limit 100 km/h a second delay range moves towards the end of the approach and in the transition area. This means, that on both lanes, the V_a drops below the value of the signalled limit much earlier without radar supervision. The illustration also shows that, at speed limit 80 km/h, the speed differences between the left and the right lane are considerably smaller than at speed limit 100 km/h.

The values for the condition with radar supervision in table 7 are arranged like table 6.

Table 7 Comparison of the average velocities at speed limit 100 km/h and 80 km/h without radar monitoring

V_a [km/h], ΔV [km/h] and a_a [m/s^2] **with radar** *(SG1 1b and 2b)*										approach		transition	
speed	cs	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	$\Delta V_{1/5}$	a_a	$\Delta V_{6/8}$	a_a
100	rl	95.8	87.7	82.3	83.5	77.9	73.7	72.4	69.7	17.9	0.17	4.0	0.27
80	rl	96.2	89.4	79.0	77.8	72.4	72.4	68.7	68.9	23.8	0.22	3.5	0.23
	ΔV	-0.4	-1.7	3.3	5.7	5.5	1.3	3.7	0.8				
100	ll	110.5	101.8	93.0	90.7	88.0	80.8	78.4	79.1	22.5	0.25	1.7	0.13
80	ll	110.6	99.6	88.5	81.8	76.7	75.4	74.9	74.3	33.9	0.35	1.1	0.08
	ΔV	-0.1	2.2	4.5	8.9	11.3	5.4	3.5	4.8				

Influence of the speed supervision:

The influence of the radar supervision is shown in the tables 8 (at speed limit 80 km/h) and 9 (at speed limit 100 km/h).

Table 8 Comparison of the average velocities at speed limit 80 km/h with and without radar monitoring

V_a [km/h], ΔV [km/h] and a_a [m/s^2] **speed limit 80 km/h** *(SG1 1a and 1b)*										approach		transition	
radar	cs	1	2	3	4	5	6	7	8	$\Delta V_{1/5}$	a_a	$\Delta V_{6/8}$	a_a
without	rl	94.5	88.6	82.7	82.0	77.3	74.7	72.1	69.8	17.2	0.16	4.9	0.33
with	rl	96.2	89.4	79.0	77.8	72.4	72.4	68.7	68.9	23.8	0.22	3.5	0.23
	ΔV	-1.7	-0.8	3.7	4.2	4.9	2.3	3.4	0.9				
without	ll	107.4	102.1	96.7	90.3	84.2	80.1	79.3	81.0	23.2	0.24	-0.9	-0.07
with	ll	110.6	99.6	88.5	81.8	76.7	75.4	74.9	74.3	33.9	0.35	1.1	0.08
	ΔV	-3.2	2.5	8.2	8.5	7.5	4.7	4.4	6.7				

Table 9 Comparison of the average velocities at speed limit 100 km/h with and without radar monitoring

V_a [km/h], ΔV [km/h] and a_a [m/s^2] **speed limit 100 km/h** *(SG1 2a and 2b)*										approach		transition	
radar	cs	1	2	3	4	5	6	7	8	$\Delta V_{1/5}$	a_a	$\Delta V_{6/8}$	a_a
without	rl	94.0	90.0	85.9	87.5	82.2	77.8	73.8	69.4	11.8	0.11	8.4	0.57
with	rl	95.8	87.7	82.3	83.5	77.9	73.7	72.4	69.7	17.9	0.17	4.0	0.27
	ΔV	-1.8	2.3	3.6	4.0	4.3	4.1	1.4	-0.3				
without	ll	109.4	103.7	98.0	96.3	93.8	83.9	83.6	83.2	15.6	0.17	0.7	0.05
with	ll	110.5	101.8	93.0	90.7	88.0	80.8	78.4	79.1	22.5	0.25	1.7	0.13
	ΔV	-1.1	2.0	5.0	5.6	5.8	3.1	5.2	4.1				

The radar supervision causes a clearer speed adaptation at speed limit 80 km/h in the approach area. The average velocities at the end of the approach area are about 5 to 7 km/h lower than without radar supervision. This results in a better speed adjustment in the transition area and in the area of the following construction site. Principally, these statements also apply to the condition with speed limit 100 km/h. According to the higher limit the speed reductions are less distinctive.

Influence on fast driving vehicles:

An essential aim of the design of the approach areas ahead of construction sites is the reduction of fast driving vehicles in order to reduce speed distribution and abrupt delays shall. The group of the fast driving vehicles is characterized by the velocity $V_{85\,\%}$.

The influences of the speed limit and the radar supervision on this vehicle group were evaluated in the following tables. They show the $V_{85\,\%}$ values in the measuring cross-sections (cs) of the approach area up to the beginning of the transition (cs6). The positions of the speed indications and the radar supervision are also expanded. Like this it is possible to see whether there is an connection between changes and the positions of signposting.

The influence of the speed limit is shown in table 10. Crucial is the condition without radar supervision (in the table on the left). Accordingly the reaction on the speed limit 80 km/h follows at cs4 and especially at cs5. At the speed limit of 80 km/h, the $V_{85\,\%}$ values exceed the speed limit (partly considerably) at the transition area. The influence of the supervision (in the table on the right) causes an earlier speed adaptation. With this supervision, the $V_{85\,\%}$ values at the end of the approach area roughly correspond to the speed limit of 80 km/h.

Table 10 Comparison of the $V_{85\,\%}$ velocity at speed limit 80 km/h and 100 km/h, without radar monitoring (left) and with radar monitoring (right)

changes of **$V_{85\%}$** [km/h] **without radar** *(SG1 1a and 2a)*							
	position:	sign 100		sign 100/80			
speed	cs	1	2	3	4	5	6
100	rl	111.0	104.9	99.8	99.8	94.9	88.0
80	rl	110.0	103.8	96.6	93.3	86.9	83.0
	ΔV	1.0	1.1	3.2	6.5	8.0	5.0
100	ll	120.0	113.9	107.8	105.7	103.0	92.0
80	ll	120.0	113.1	106.2	101.4	93.3	88.0
	ΔV	0.0	0.8	1.6	4.3	9.7	4.0

changes of **$V_{85\%}$** [km/h] **with radar** *(SG1 1b and 2b)*							
	position:	sign 100		sign 100/80			
speed	cs	1	2	3	4	5	6
100	rl	112.0	99.8	92.8	94.9	88.5	83.0
80	rl	112.0	101.4	89.6	86.9	80.5	80.0
	ΔV	0.0	-1.6	3.2	8.0	8.0	3.0
100	ll	122.0	112.5	103.0	98.1	98.1	88.0
80	ll	122.0	110.1	98.1	91.7	83.7	81.0
	ΔV	0.0	2.4	4.9	6.4	14.4	7.0

At speed limit 80 km/h (left table) a reaction to the signposting of the supervision (after QS3) can be observed. The speed limit is met on the right lane at the end of the approach area and on the left lane at the beginning of the transition, also by the group of the fast vehicles. Without radar supervision this is not the case at any cross-section.

Also at speed limit 100 km/h (right table) the speed adaptation is spread rather equal in opposite to the condition without supervision. On the right lane, a reaction on the radar indication (cs2) can be mentioned. From this point the speed limit is met on the right lane. On the left lane it is met only in front of the radar cab (cs4).

Table 11 Comparison of the $V_{85\,\%}$ velocity without and with radar monitoring, at the speed limit 80 km/h (left) and 100 km/h (right)

changes of **$V_{85\%}$** [km/h] **speed limit 80 km/h** *(SG1 1a and 1b)*							
	position:		indication radar			radar cab	
radar	cs	1	2	3	4	5	6
without	rl	111.0	103.8	96.6	93.3	86.9	83.0
with	rl	112.0	101.4	89.6	86.9	80.5	80.0
	ΔV	-1.0	2.4	7.0	6.4	6.4	3.0
without	ll	120.0	113.1	106.2	101.4	93.3	88.0
with	ll	122.0	110.1	98.1	91.7	83.7	81.0
	ΔV	-2.0	3.0	8.1	9.7	9.6	7.0

changes of **$V_{85\%}$** [km/h] **speed limit 100 km/h** *(SG1 2a and 2b)*							
	position:		indication radar			radar cab	
radar	cs	1	2	3	4	5	6
without	rl	110.0	104.9	99.8	99.8	94.9	88.0
with	rl	112.0	99.8	92.8	94.9	88.5	83.0
	ΔV	-2.0	5.1	7.0	4.9	6.4	5.0
without	ll	120.0	113.9	107.8	105.7	103.0	92.0
with	ll	122.0	112.5	103.0	98.1	98.1	88.0
	ΔV	-2.0	1.4	4.8	7.6	4.9	4.0

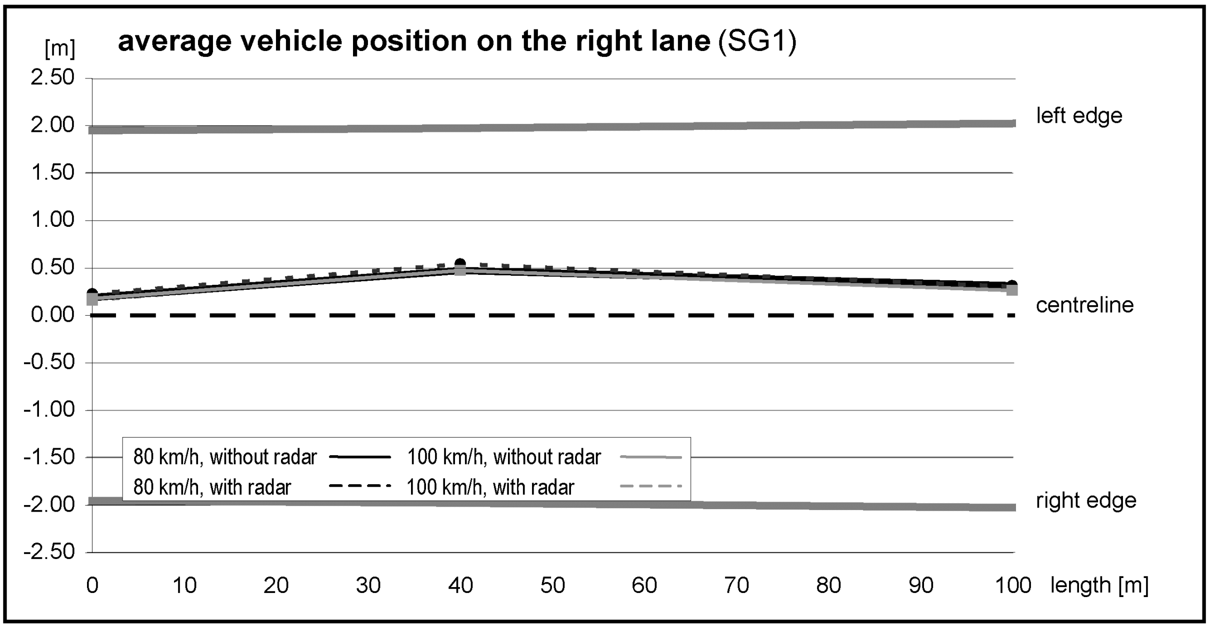
As expected, the $V_{85\,\%}$ speeds decrease significantly along the examination stretch. The differences between the beginning of the approach area (cs1) and the beginning of the transition (cs6) in the condition without supervision amount 22 to 28 km/h on the left lane and 28 to 32 km/h on the right lane. The greatest differences appear at the condition with speed limit 80 km/h. As stated at the V_a values already, these differences increase considerably with radar supervision (on the right lane 29 to 32 km/h; on the left lane 34 to 41 km/h).

5.2.3 Track behaviour

The track behaviour is examined at the beginning, in the middle and at the end of the entry circular arc of the transition area. The evaluation is done with the trace distribution (expressed by the standard deviation of the average position of the vehicle axes) and with the average position of all vehicle axes. The latter refers to the lane keeping compared to the ideal situation in the middle of the lane.

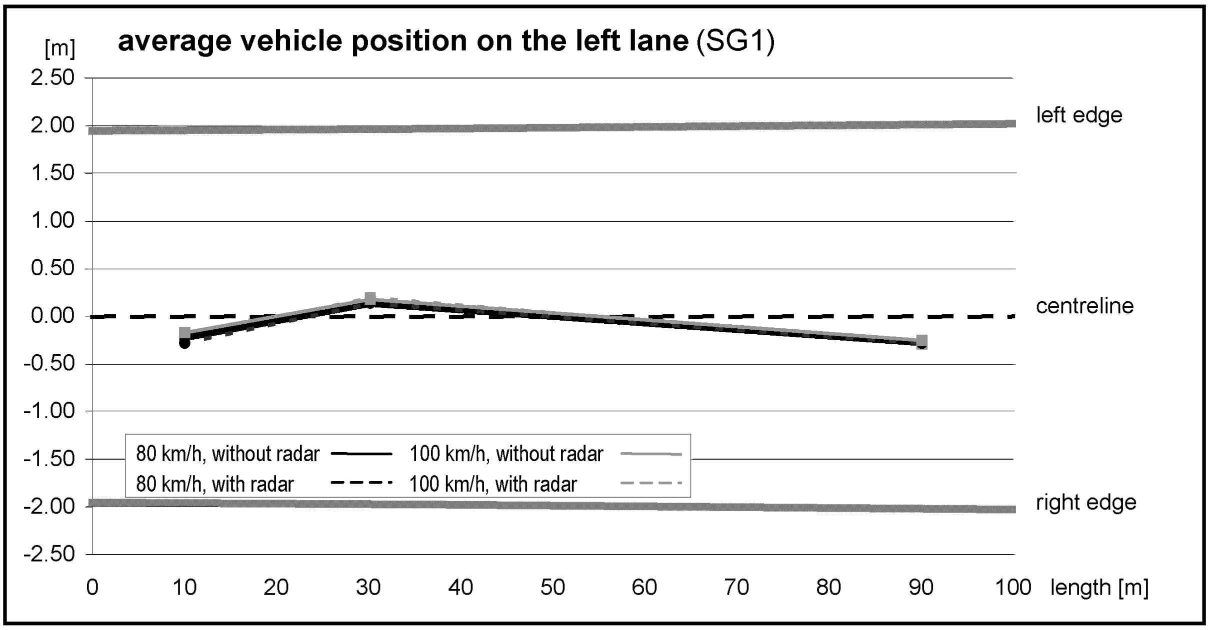
The following two figures show the displacement of the average position of the vehicle axis compared to the lane middle in the three cross-sections (entry, middle and exit) of the introduction arc. The evaluation is carried out separately for the right lane (cf. fig. 6) and the left lane (cf. fig. 7). From the illustrations it is obvious, that the vehicles on the left lane drive on the left side of the centreline of the lane and vehicles on the right drive on the right side of the centreline of the lane.

Figure 6 Average vehicle position on the right lane



Without reference to the signalled speed limit and its supervision, on the right lane a clear deviation to the left in the area of the three observation cross-sections. While the vehicle axis is approx. 0.18 m on the left to the centreline at the beginning of the circular arc, the corner is cut to approx. half a metre in the middle of the circular arc. At the end of the circular arc the average vehicle axis is approx. 0.30 m to the left of the centreline. The complete displacement is approximately 0.50 m. Regarding the signalled speed limits of 80 and 100 km/h and the speed supervision (without/with radar), no differences in the average position of the vehicle axis were found.

Figure 7 Average vehicle position on the right lane



In all of the test setups the corner is cut on the left lane too, but compared to the right lane with a rather small displacement of 0.20 m to the left. Before this (at 0 m) the vehicles swing out to the right (0.20 m). At the exit of the circular arc (at 90 m) the vehicle axis is approx. 0.25 m to the right of the centreline again. This behaviour yields a complete displacement of approx. 0.80 m.

All four tests show constant standard deviations (S). The differences between the tests are on both lanes significantly below the measuring precision of 4 cm. Also along the transition area the differences between the S-values are marginal. Only on the left lane a slight rise of the trace spread results in the exit of the introduction arch.

The influence of the speed supervision on the lane keeping is extremely small. Altogether, neither the speed limit nor the speed supervision shows any influence on the displacement of the vehicles regarding to the centreline.

5.2.4 Lane changes

For lane change events the frequency of potential danger situations between the single trials were examined. Lane changes were estimated to be dangerous, if at least one of the involved vehicles had to decelerate.

At SG1 most of the lane changes happened because of width restriction on the left lane in the construction site area. In this case more changes happened from left lane to right lane than reversed. As reference value for the frequency, the complete load (number veh. per cross-section) is used during the test duration. Approx. 100 to 150 lane changes could be observed hereof between approx. 3 and 30 lane changes with braking. The share of lane changes was less than approx. 10 % of the complete load, the one of lane changes with braking less than approx. 2 %.

The shares of lane changes (lc) and lane changes with braking at the different experimental setups are compared in table 12.

Table 12 Comparison of lane changes

	comparison speed limit 80/100 km/h				**comparison without/with radar**			
	80/100 km/h **without radar**		80/100 km/h **with radar**		**80 km/h** without/with radar		**100 km/h** without/with radar	
changes in % of complete load	80 km/h (SG1 1a)	100 km/h (SG1 2a)	80 km/h (SG1 1b)	100 km/h (SG1 2b)	without radar (SG1 1a)	with radar (SG1 1b)	without radar (SG1 2a)	with radar (SG1 2b)
% all changes	8.4	8.4	7.9	10.7	8.4	7.9	8.4	10.7
% changes with braking	1.8	1.5	2.1	0.3	1.8	2.1	1.5	0.3

Comparing the speed limits 80/100 km/h, the frequency of lane changes is about equal. With radar supervision, at speed limit 100 km/h, a little higher frequency of lane changes was observed than at speed limit 80 km/h. Nearly all changes were executed without braking.

6. Analysis

In this chapter the different influences on the traffic flow are analyzed. These can be divided into influences due to the trial layout (e.g. signalled speed limit or type of the channelizing devices used) and influences due to the local features of the single examination stretches. These also concern geometric features which, till now, were not taken into account. The following influences were considered to be essential:

- The lane width in the approach and connection area
- Lateral distances between the channelizing devices and the edge of the lane
- Opening length of the crossing of separation strips and the angle of turnaround

In a first step, it is checked which of the mentioned changes are significant in the statistical meaning. Conspicuous changes that were already mentioned in chapter 5 were of special interest. In a second step, the possible explanations for statistically significant and safety relevant changes are sought. The safety relevance is considered to be essential regarding possible suggestions for improvement concerning the design of the construction sites.

In chapter 5 the measurement results were evaluated separately for the individual examination stretches. In the following analysis comparisons also are made between the examination stretches - where possible and reasonable.

6.1 Statistical tests

The evaluation of the change of the according values was carried out with the following tests for statistical significance:

F-Test

Comparison of two variances from normal distributed parent populations.

ANOVA (Analysis of Variance)

Variance analytical comparison of expected μ.

Besides the sequential, isolated analysis of single influences, several combined influence factors were also looked at (multifactorial ANOVA). Here the real strength of the ANOVA is brought out because significances can be stated for separate influence factors and for their interactions, too.

Level of significance α

Due to the sample sizes of the individual trials (about 1000 vehicles per measurement and cross-section), a significance level of 0.01 (1% error probability) was chosen.

7. Conclusions

7.1 Accident occurrence

The considerable differences of accident frequency between individual construction zones on freeways indicate, that it is basically possible to improve safety with suitable methods. This was shown on the experimental setups with different channelizing and separating devices as well as the use of speed supervision.

Inside areas of construction zones with the operation forms 4+0 and 3+1 without junctions do not show any increased accident frequency in comparison to the state without road works, if the two carriageways get structurally separated by construction zone barriers. This conclusion applies to motorway sections of a DTV up to 50 000 veh/day.

An increased need for action consists in the design of junctions in construction zones. These are often established with low care in comparison to the crossing of separating strips. Because of this, many accidents happen in this area.

The outstandingly frequent accidents at night require efforts on the improvement of visual guidance in the construction zones. This demand refers to the arrangement of the crossing of separating strips, the inner area of the construction zone, and as already mentioned the junctions in the area of construction zones.

The previous accident evaluations have also shown that traffic routing with any kind of lane drop should be avoided. Already at average traffic loads, lane drops can cause an excessive rise of accident frequency.

7.2 Traffic flow

The following demands are formulated for the quality of the traffic flow in the approach area in front of the construction site:

- The vehicle speeds shall decrease as far as, with regard to the trafficability of the transition area, at the end of the approach area an adequate speed level can be obtained. The speed level should be adapted to the signalled speed limit and to the geometry of the transition area. The speed adaptation shall proceed gradually.
- The speed reduction results in homogenization of the speed distribution.
- In the transition area the speeds should not drop further and no abrupt braking should happen.

- The speeds should be distributed homogeneously and similar along the transition area. This demand applies analogously to the trace distribution.

The order and design of the approach areas in front of construction zones needs to be compliant to fulfil the demands above.

The arrangement of a construction zone portal applies to the approach area, the channelizing devices and the lights conditions only apply to the transition area.

7.2.1 Speed limit

The signalled speed limit of 80 km/h is not met by more than the half of all vehicle drivers at the end of the approach area. At speed limit 100 km/h this only concerns approx. 15% of the drivers.

About one third of the complete speed adaptation is done in the area of the last speed signal in front of the transition area, independently of the height of the speed limit.

The signalled maximum speed in the transition area is not met at speed limit 80 km/h by approx. 30% of all vehicles while it is met by most vehicles at speed limit 100 km/h.

With regard to the delay behaviour, the speed limit has no influence inside the transition area because at both speed limits the speed reduction is done mainly in front of the transition area.

When comparing the signalled speed limits, the difference of the average speeds in the access area is smaller than the difference of the signalled speed limit (20 km/h). An excessive impact on the fast vehicles cannot be expected. These conclusions also apply to the transition area. The speed level is also depending on the geometry of the transition.

The limited effect on the speed level in the construction zone with speed limit 80 km/h has to be taken into account. On the other hand, a speed limit of 100 km/h causes no safety relevant drawback of the speed behaviour.

The placement of the last speed signal 350 m in front of the transition, as recommended in the existing Swiss standard, proves to be suitable.

Different speed limits in the approach area do not influence the variance of the vehicle speeds fundamentally. Also no local effect of the speed signal on the homogeneity could be established.

Independing of the speed limit, practically no more homogenization of the speed distribution takes place in the transition area. Compared to other influences (e.g. the type of the channelizing devices) the effect of the speed limit on the speed distribution is marginal.

7.2.2 Speed supervision

The speed reductions at a certain speed limit, due to radar supervision are comparable to those achieved with a reduction of the speed limit by 20 km/h. As opposed to the influence of speed limit, when using radar supervision

- the speed limit of 80 km/h at the end of the approach area is also met by fast vehicles and
- the homogeneity of the speed distribution is considerably improved.

Both, the announcement and the visible presence of the supervision device are considered to be essential for the effectiveness.

Placing the radar device 125 m in front of the transition area proved to be suitable.

7.2.3 Construction side portals

The contribution of the portals to attract attention cannot be neglected. However clear effects on the speed behaviour are not to be expected.

The positive experiences from outside Switzerland cannot be confirmed. The effectiveness of the portals adapts presumably only in combination with flashing lights positioned on top.

7.2.4 Channelizing devices

Neither on the speed level nor on the compliance with the speed limit, any general influence of the channelizing devices can be stated.

The relevant speed adaptation is done at all tests directly in front of the transition area, independing of the channelizing devices.

With channelizing rails and low marker buoys more homogeneous speed progressions arise in the connection. Compared to channelizing rails, with high marker buoys an erratic speed reduction causing a more inhomogeneous traffic flow is observed.

The type of channelizing facilities has no essential influence on the speed variance at normal lighting conditions (during the day). There is a tendency towards more homogeneous traffic flow by using channelizing rails.

In comparison to the high marker buoys, a considerably better vehicle guidance can be obtained in the transition area with channelizing rails and low marker buoys.

Larger opening lengths challenge for faster driving at the transition area. The trials have shown that some vehicle drivers use this possibility. At opening lengths of over 100 m a speed limit of 80 km/h is not met to at the end of the transition area from approx. 50 to 70% of all drivers.

The larger the lane widths in the transition area, the higher the measured speed in this section. For a tight track behaviour wide lanes are to avoid in the transition area. A swimming effect in the track behaviour arises at lane widths of more than 4.0 m and driving room widths between the channelizing facilities of 10.0 m.

An effect of the additional construction zone barrier behind the marker buoys on speed behaviour could not be stated. However positive effects stand out on the trace behaviour.

7.2.5 Lighting conditions

As opposed to daytime, uneven speed progressions appear at night. These irregularities show uncertainties in the visual guidance at both kinds of channelizing device. They are much more obvious with high marker buoys than with channelizing rails with low marker buoys.

The guidance function of the (linear) channelizing rail with low marker buoys is during the day, but primarily at night better than with (dot-like) high marker buoys. The linear form of the carriageway markings in the transition area, at which the large marker buoys are built along, cannot compensate the mentioned guidance disadvantage adequately.

Channelizing rails and low marker buoys cause altogether a better and earlier speed adaptation and a slighty more continuous way of driving in the transition at darkness.

The construction site, in terms of obstacle, is perceived earlier at night with high marker buoys. Presumably, this also is the reason for the considerably stronger delay in front of the transition area than with low marker buoys. The routing of the transition area cannot always be perceived on time because of occlusion and dazzling effects at the drivers eye-level.

7.2.6 Further factors

The items described below, regarding the development of measures for construction zones, descend mainly from conclusions of examinations undertaken abroad. Besides the construction zone portals it covers suggestions for the design in the approach area and the transition area.

The locations of the speed signals as recommended in the existing Swiss standard are considered to be suitable. As a rule, the grading of the speed limit with two displays is sufficient.

With a funnel-shaped road limitation towards the end of the approach area, a speed adaptation and homogenization similar to the one with radar supervision can be realised.

8. References

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