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dedicated to

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Analysis of Eye-Movement Behaviour Using Moveable Headlamps

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1. Introduction

In the last few decades car headlamp systems have only slightly improved. The driver only has the choice between low and high beams and to switch on the fog lamps during adverse weather conditions. These systems are far more powerful than conventional light filaments replaced by halogen filaments and even more so now with gas discharge lamps have been introduced. Due to special lenses, projection headlamps, and free-form reflector technology, utilization of the light quantity has been increased by thirty to seventy percent. However, the headlamp system itself has remained essentially unchanged. The ability to direct the available light dynamically in the direction it is actually needed has remained only a wish. The question now is on which parts of the road the driver of a vehicle actually needs the light.

Ninety percent of the information needed to drive a car is acquired by the driver's eyes. But up to now it is not fully understood which information the driver really needs and also, where he will find this information in the environment.

Many papers quote the fixation behaviour and fixation distances of a car driver during the hours of daylight [1, 2, 5]. Regarding eye-movement behaviour at night, however, only a few investigations have been taken [1, 4]. Until now very little is known about the eye-movement behaviour in bends after dark [11].

The Department of Lighting Technology at Darmstadt University of Technology and the Research Department of BMW AG therefore commenced a research project to obtain more information and details about the fixation behaviour of car drivers at day and night.

One requirement of the research project was to find out if and in which range it is possible to measure and quantify the influence on the fixation behaviour of a car driver if moveable headlamps are used. A second point was to establish the differences in eye-movement behaviour when using different light sources (halogen filament lamp (HFL) / gas discharge lamp (GDL)).

2. Moveable Headlamp Systems

A BMW E38 (7 series) was used as the test car. The car was equipped with a Dornier Eye-Tracking-System and a control system for the moveable headlamps.

The newly developed moveable headlamps are controlled by path prediction based on the vehicle's dynamics and navigation data [7, 8, 9]. Using the output from the path prediction model, it is possible to control the moveable headlamps appropriately.

Figure 1 shows the path prediction structure. Prediction of the path is estimating the lateral disturbances or accelerations acting on the vehicle body. A prediction of the future path of the vehicle based on the current vehicle dynamic is obtained in combination with a simple model of the vehicle. A filter has been added so that the variations in the prediction of the future path, e.g. due to steering wheel motions, can be kept under control.

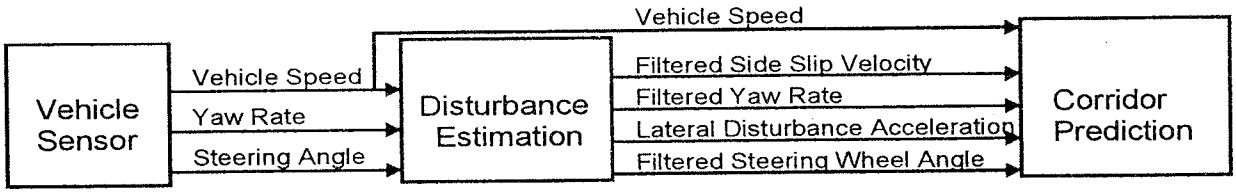

Figure 1: Dynamic corridor prediction structure

The light distribution of series-production car headlamps were used as a basis for the construction of moveable headlamps. For the various investigations a

- headlamp with a halogen filament lamp H1 (HFL) and a
- gas discharge headlamp (GDL)

were used.

The moveable headlamps were modified in such a way that the projection system was able to rotate horizontally with the help of servo motors. In this construction the whole reflector with the light distribution is moveable. The only small change in the light properties was an elliptical shaping of the outer lens in order to have enough space for the rotation of the projection lens (see Figure 2). The possible rotation angle of this moveable headlamp was $\varepsilon = \pm 20°$.

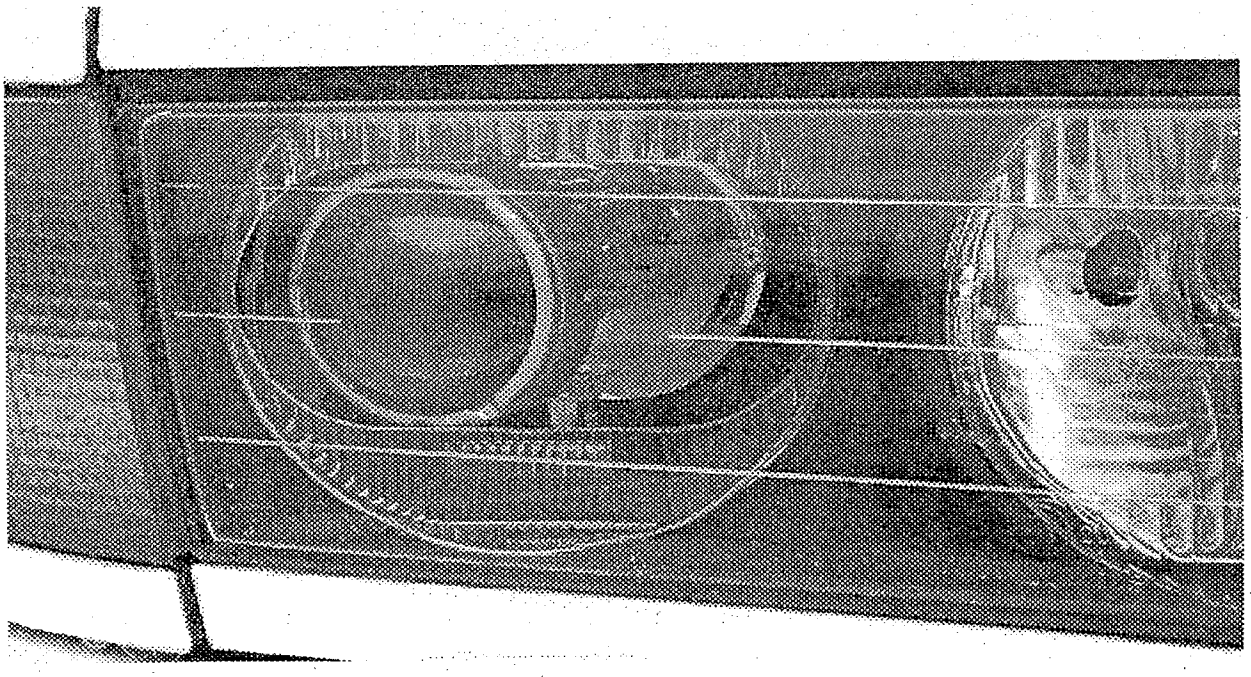

Figure 2: Picture of the moveable headlamps used, equipped with a gas discharge lamp (GDL). The reflector is rotated as far as possible right (about $\varepsilon = 20°$).

3. Test - Conditions

To measure the eye movement and the fixation behaviour of a driver under constant conditions, the investigations have been carried out on a standard test track. This standard test track is a circuit with a length of d = 8 km and with defined bends etc. One of the most important benefits is that on the test track there is no additional traffic (ahead, behind, oncoming), and therefore there is no influence on the eye movement behaviour by additional traffic. The

measurements were taken in good weather conditions.

Ten test persons took part in this experiment. All of them had more than 50,000 km driving experience and normal or corrected normal vision. During measurements on the test track the eye movement behaviour of the test persons varied according to the following five conditions:

- daylight - without headlamps
- night - time - with standard halogen headlamps (HFL)
  - with moveable halogen headlamps (moveable HFL)
  - with standard gas discharge headlamps (GDL)
  - with moveable gas discharge headlamps (moveable GDL)

The Eye-Tracking-System (ETS) is based on the relative infrared cornea reflexes. It consists of two IR-illuminators (on the dashboard at left and right) which have different shapes. A module with a camera is installed directly in front of the driver to track his right eye. In front of the eye camera a mirror system is mounted which is adjustable in two axes. Based on an image processing, the mirror is moved so that the driver's right eye remains in the center of the eye camera. The fixation point is calculated from the relative position of the pupil and the IR-reflexes on the cornea. In addition to the eye-camera, a so-called scene camera is mounted near the driver's head (height $h_E = 1.17$ m).

The calculated fixation position is displayed from the ETS on the scene video as a white cross and is recorded in a file form of x-y coordinates relative to the calibration points.

By means of a special calibration process it is possible to convert the pixel coordinates to an angle of view direction (from the perspective view of the driver) and to a fixation distance.

The width of the road lane was $b = 3.75$ m. The mounting height of the headlamps was $h_H = 0.65$ m.

4. Eye Movement Behaviour

The eye movement behaviour is recorded by the Eye Tracking System. In combination with the information about sections of the road, fixation behaviour at special parts on the test track is analyzed.

Before the described experiments are conducted the ETS data had been evaluated on different road types (spatio-temporal) [2]. In this paper controlled investigations on straight roads, left-hand and right-hand bends are discussed, the radius of the bends is constant with r = 110 m.

The representation of the fixation measurements when driving through part of a road is shown for example in Figure 3. In part a) the fixations are shown over the driving distance (bird´s view presentation), in part b) the fixations are integrated over time and are displayed as one fixation area in the driving scene (perspective view).

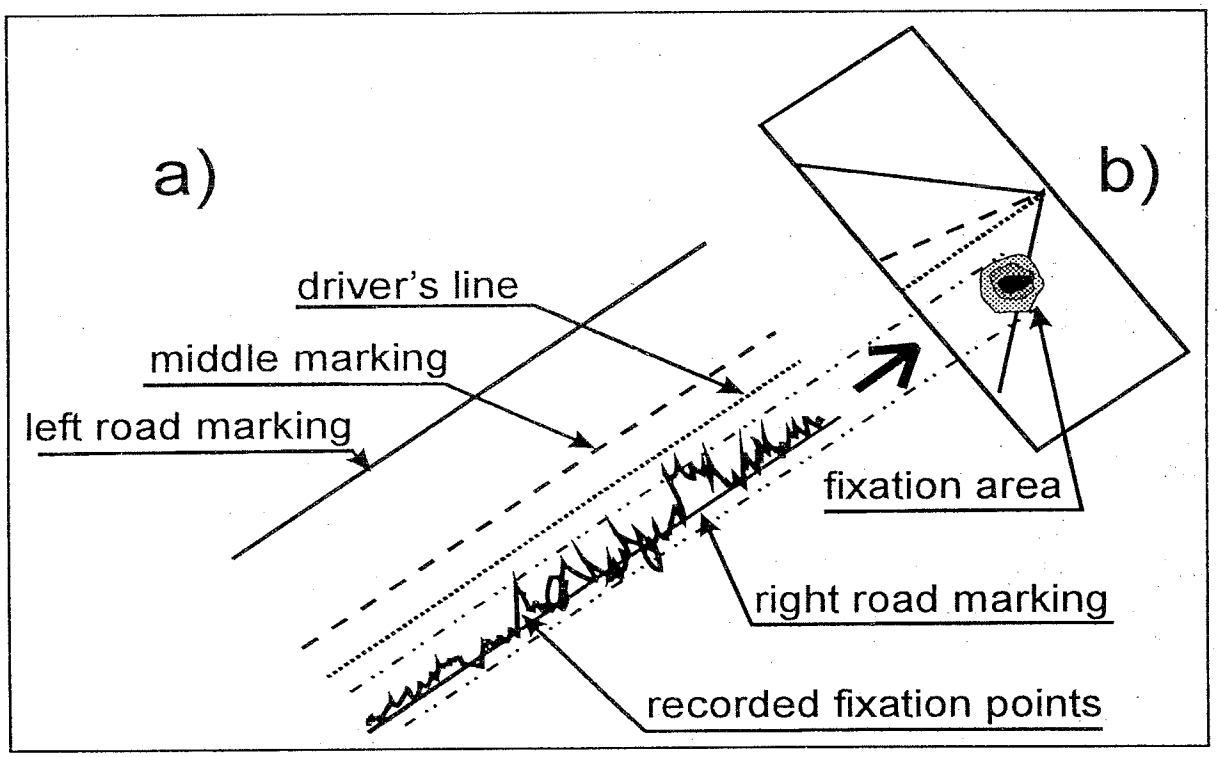

Figure 3: Example of the fixation behaviour when driving on a straight road

a) Bird's view presentation
b) Perspective view of the driver

By integration over time the most frequently occured areas are identified. The x-y coordinates of the ETS are converted to angle coordinates (α, β) with the origin at the position of the driver's head. This converted data is plotted in Figure 4. In this figure and in the following figures the single measurements are standardized to compare the figures correctly (white 0%, black 100%). In addition, the 90% and 50% fixation areas of the measurements are shown in the presented figures. To give an impression of the road geometry in the figures, the road markings are plotted as well as lines for different distances in front of the car. The point with a high frequency of fixation occurrences is called fixation accumulation point (FAP). The FAP is marked with two dotted lines (see Figure 4).

To permit a statement about the spread of the eye movement in spatial terms, the area factor A_{f50} is defined. The area factor describes the relationship between the complete field of vision for the driver ($\alpha = \pm 20°$; $-6° < \beta < 1°$) and the area which the driver used for 50% of the fixations (see Figure 4; *50% area*).

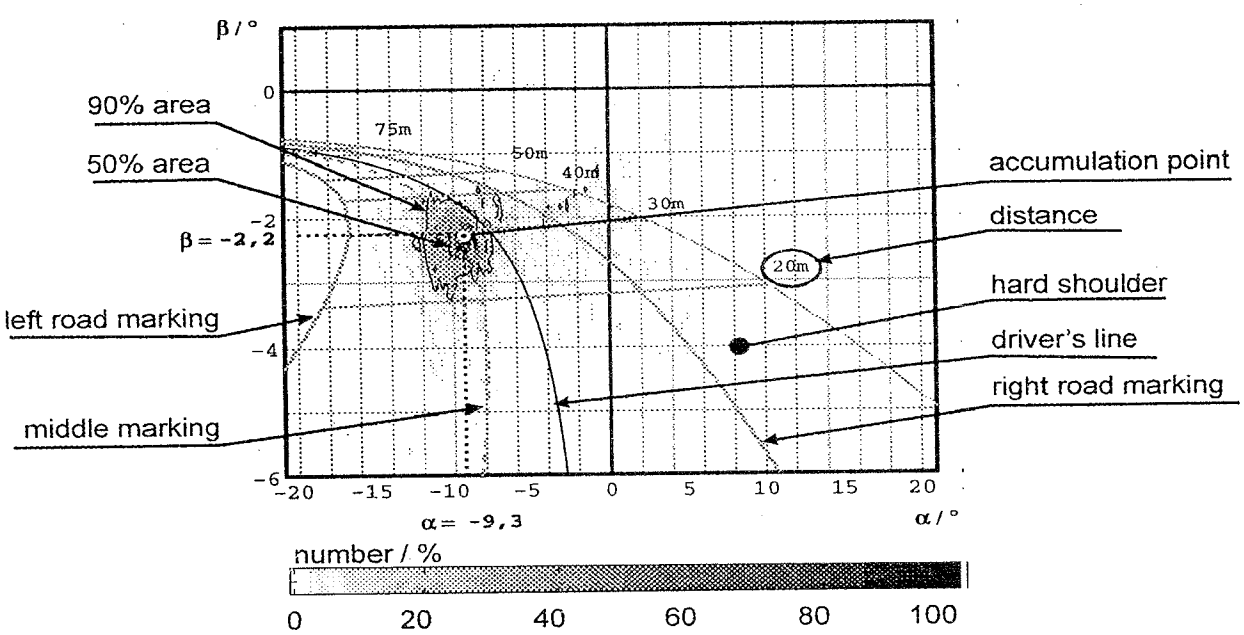

Figure 4: Example of integrated fixation points of one driver for several trips of the same bend.

In every figure more than 3000 single measurements are plotted (same person drove road part several times). The measurements shown in the following figures are all from the same test person.

4.1 Daylight Driving

The first experiment was driving on a straight two-line road with a hard shoulder at daylight without additional traffic and without changing conditions. The fixation accumulation point (FAP) distance is as far as possible (90-100 meter). The small spread around the FAP can be easily recognized in Figure 5.

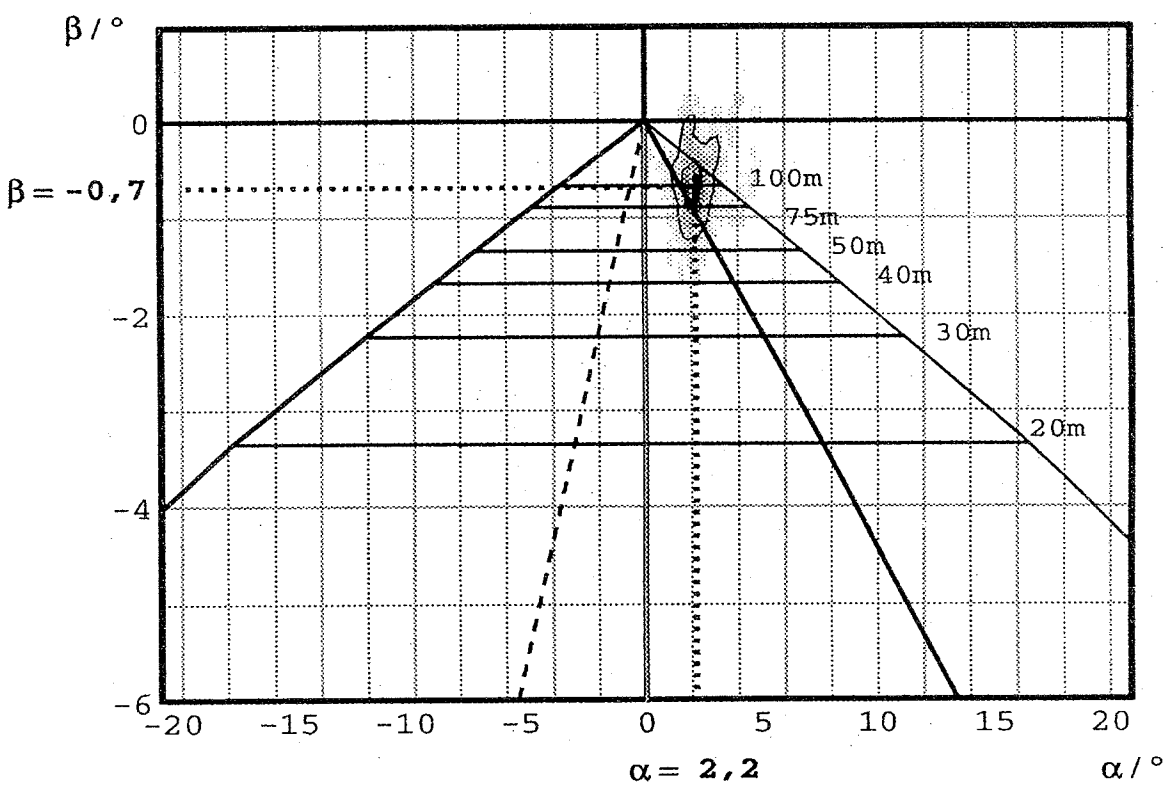

Figure 5: Fixation area when driving on a straight road at daylight.
Fixation direction: $\alpha = 2.2°$ $\beta = -0.7°$
FDAP[1]: $d = 95.8$ m
Area factor: $A_{f50} = 0.10$

[1] FDAP: Fixation Distance Accumulation Point

Eye movement behaviour changes considerably when a driver approaches a bend. The driver begins to receive information from the course of the road in the bend (e.g. bend radius).

In the bend the driver appears to obtain information about the course of the road from the tangent of the inside radius and the outside edge of the road. The fixation distance accumulation point (FDAP) for a left-hand bend is at d = 34.6 m (see Figure 6) and for a right-hand bend at d = 38.2 m (see Figure 7). Figure 6 and Figure 7 show also, that the driver is scanning the road for an optimal lane keeping. For the left-hand bend the FAP is on the center of the road, for the right-hand bend the FAP is on the right-hand side.

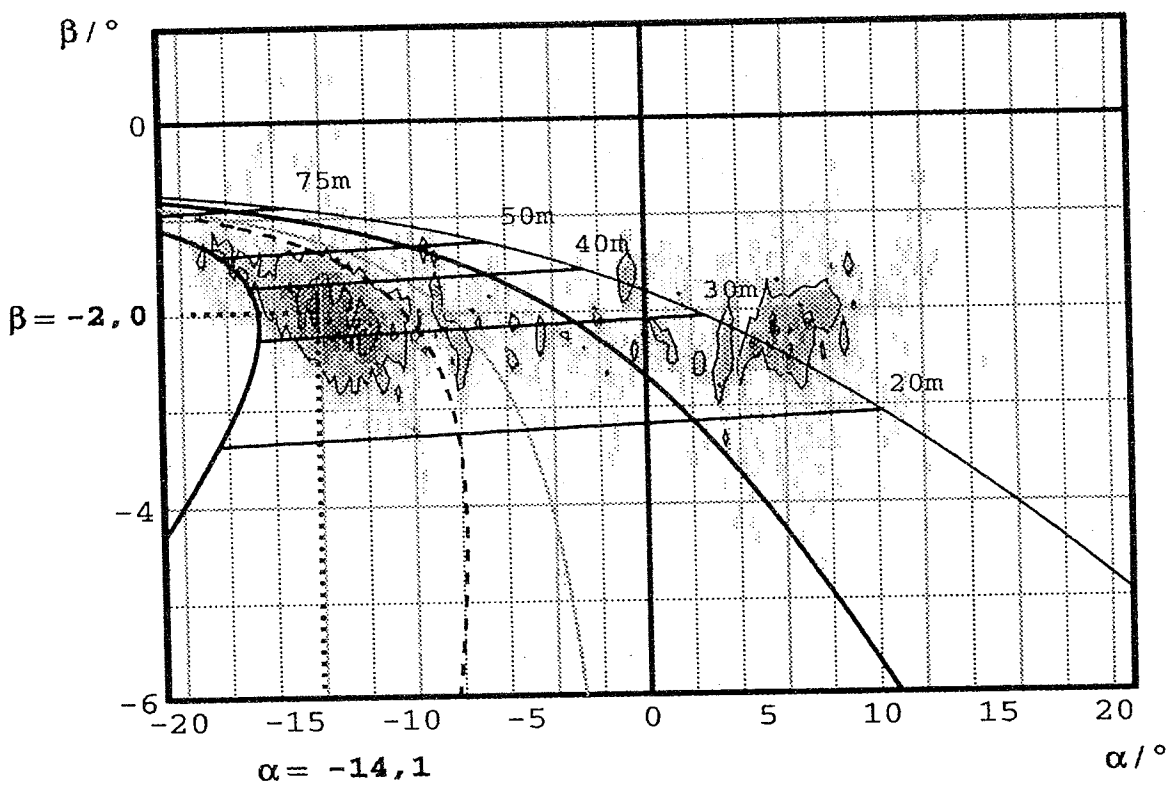

Figure 6: Fixation area when driving through a left-hand bend at daylight.

Bend radius	*r = 110 m*	
Fixation direction:	*α = -14.1°*	*β = -2.0°*
FDAP:	*d = 34.6 m*	
Area factor:	*A_{f50} = 0.81*	

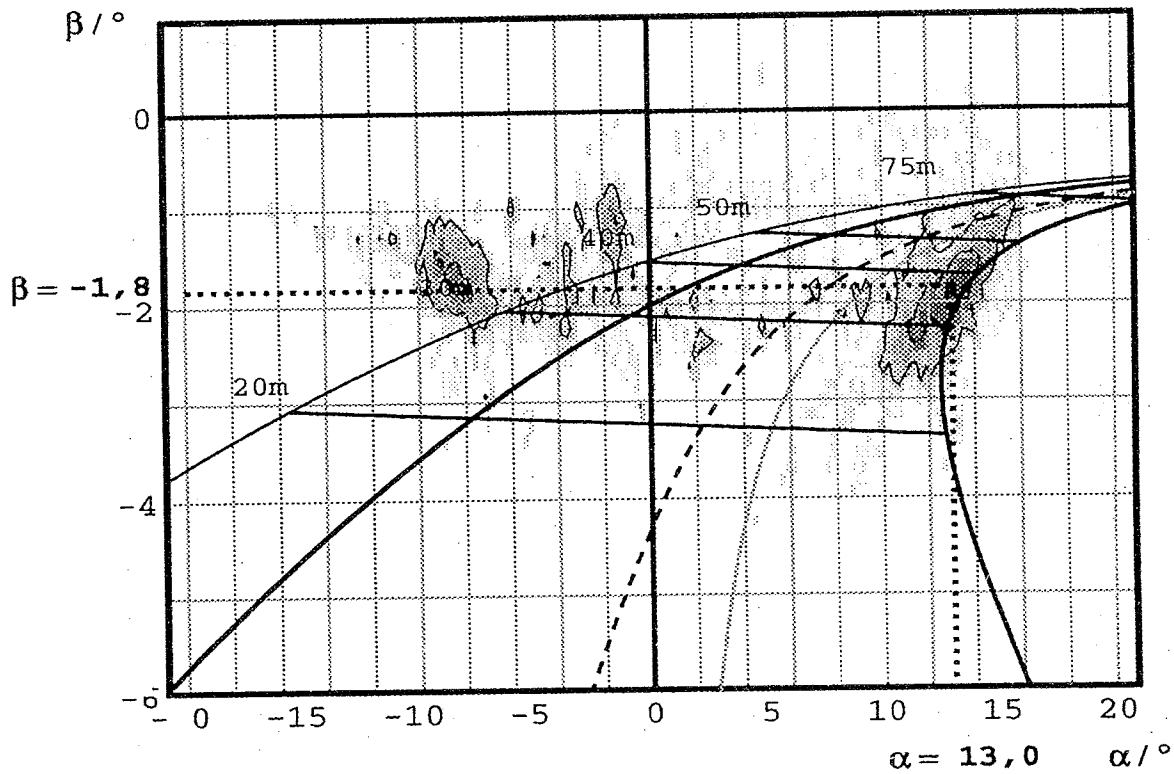

Figure 7: Fixation area when driving through a right-hand bend at daylight.
Bend radius $r = 110$ m
Fixation direction: $\alpha = 13.0°$ $\beta = -1.8°$
FDAP: $d = 38.2$ m
Area factor: $A_{f50} = 0.71$

4.2 Night-Driving - Standard Headlamps

4.2.1 Halogen Headlamps at Night

At night the eye-movement behaviour of the driver changes considerably due to the reduction of the accompanying information. This is one of the reasons for the reduction of the FDAP on straight roads by about fifty percent to a distance of d = 47.9 m. The position of the accumulation point is, as expected, only in a short distance in front of the cut-off-line of the headlamps on the road.

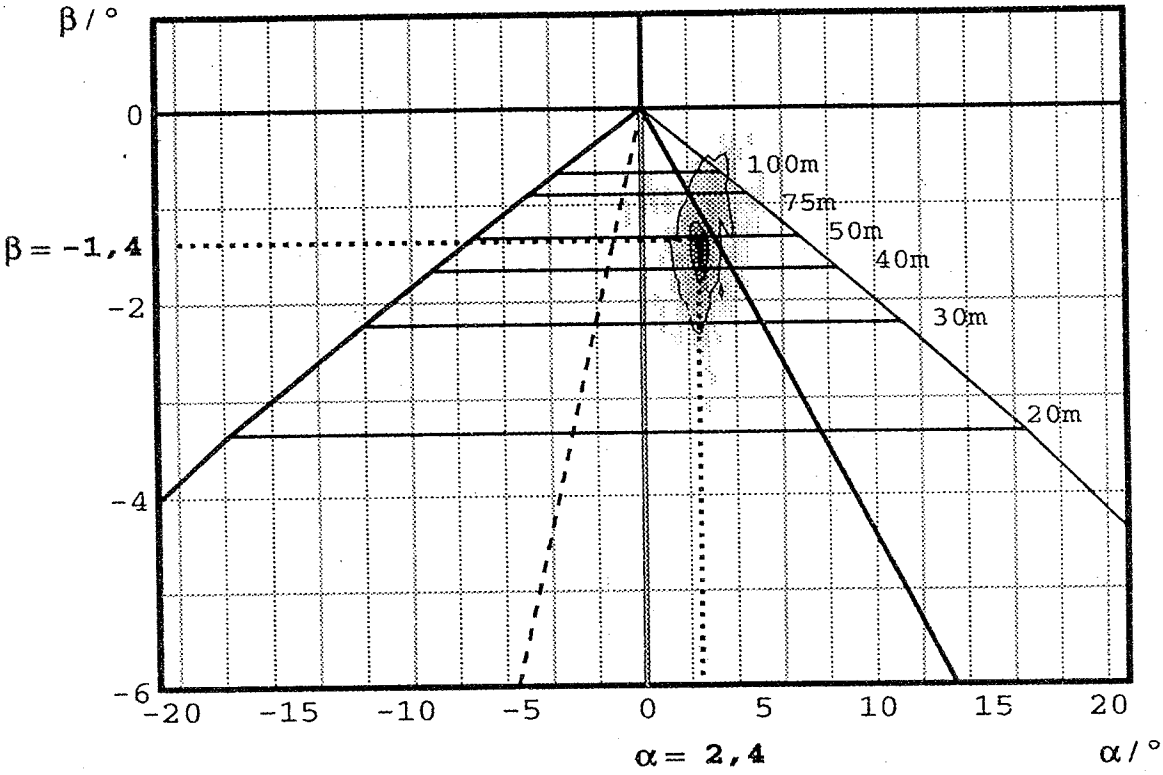

Figure 8: *Fixation area when driving on a straight road at night.*
Headlamp system: standard halogen low beam (HFL)
Fixation direction: $\alpha = 2.4°$ $\beta = -1.4°$
FDAP: $d = 47.9$ *m*
Area factor: $A_{f50} = 0.14$

Two effects could be described, when driving with standard halogen headlamps (ECE) through bends. The reduction of the illuminance on the road results in a reduced distance between the car and FAP (see Figure 9, d = 23.6 m). Another effect is the increased spread of the fixations. The driver collects more information for lane keeping, this is shown in Figure 9.

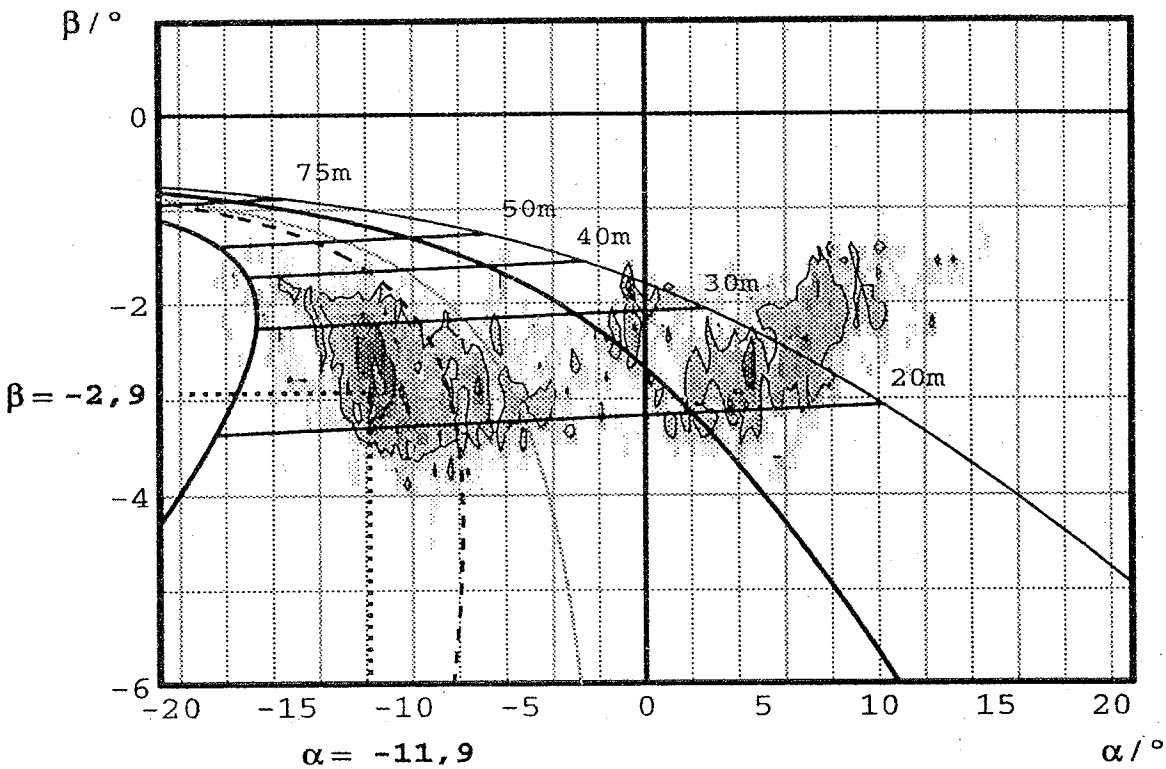

Figure 9: Fixation area when driving through a left-hand bend at night. The reduction of the perceptable environment leads to an increase of the field of interest (two FAPs left and right), which are in less distances.
Headlamp system: standard halogen low beam (HFL)
Bend radius $r = 110$ m
Fixation direction: $\alpha = -11.9°$ $\beta = -2.9°$
FDAP: $d = 23.6$ m
Area factor: $A_{f50} = 0.88$

The fixation behaviour in right-hand bends at night with standard halogen headlamps (HFL) has the same characteristics as for left-hand and right-hand bends. Through the reduction of the visible surrounding the driver searches for the information about the road ahead in a fewer distance in front of the car. The field of fixations increases, the area factor changes from $A_{f50} = 0.14$ to $A_{f50} = 0.88$. These are the reasons for two FAPs: one on the right-hand road border and the other at the left-hand road border (outside edge of the bend). Both FAPs are at a distance of about d = 25.4 m. The figures show also, that the driver needs two fixation areas for lane keeping by using the standard halogen low beam system. The driver has to look on the right-hand and left-hand side of the road to keep the lane.

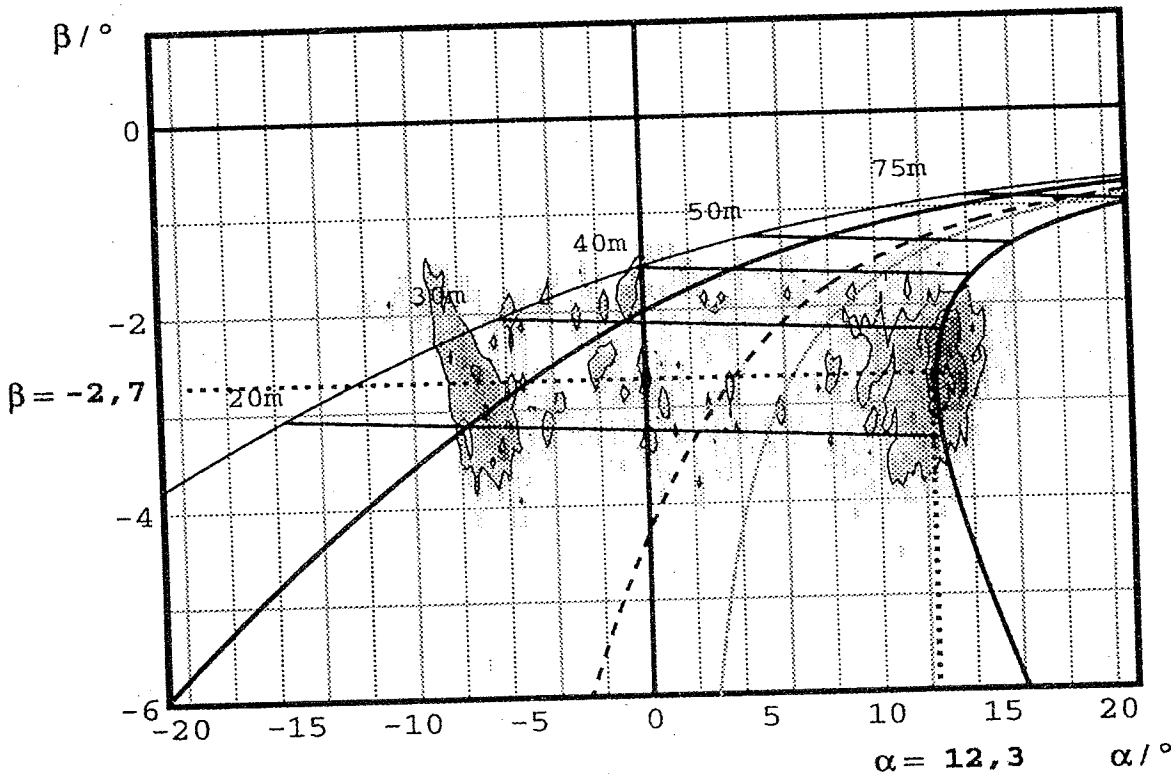

Figure 11: When driving through a right-hand bend at night-time with HFL there are two fixation areas (FAPs). The two fixation distances accumulation points (FDAP) and the large areas of interest could be seen very clearly.

Headlamp system:	*standard halogen low beam (HFL)*	
Bend radius	*r = 110 m*	
Fixation direction:	$\alpha = -12.3°$	$\beta = -2.7°$
FDAP:	*d = 25.4 m*	
Area factor:	$A_{f50} = 0.64$	

4.2.2 Gas Discharge Headlamps at Night

As already known, the luminous flux of GDLs is three times greater than the HFLs, also the light distribution is different from the halogen version. The area in front of the car is brighter, the light distribution is fundamentally more extensive and the brighter area in front of the car is responsible for a change of the adaptation level of the driver and the contrasts on the road. Both parameters have a considerable influence on eye-movement behaviour.

The eye-movement pattern when driving on a straight road with GDL is wider than with HFL and the FAP drifts to the driving line, which is the middle of the road (see Figure 11).

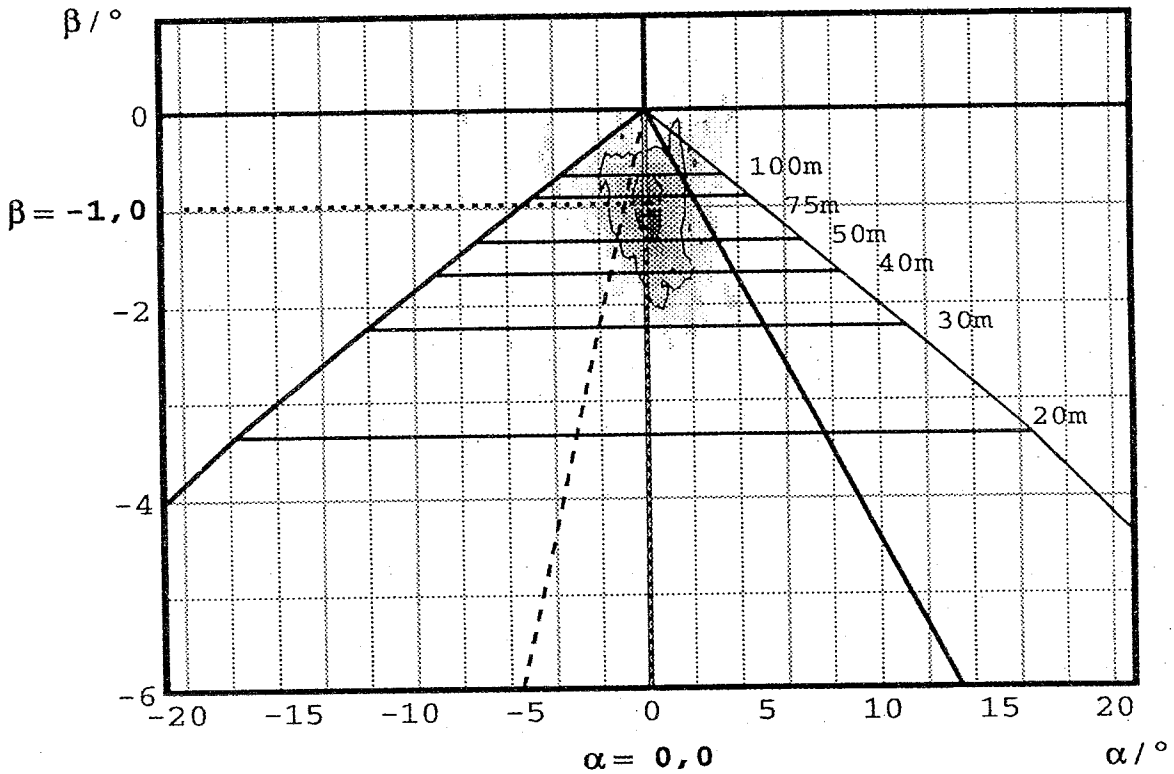

Figure 11: One fixation area when driving on a straight road at night with GDL.
Headlamp system: gas discharge low beam (GDL)
Fixation direction: $\alpha = 0.0°$ $\beta = -1.0°$
FDAP: $d = 67$ m
Area factor: $A_{f50} = 0.22$

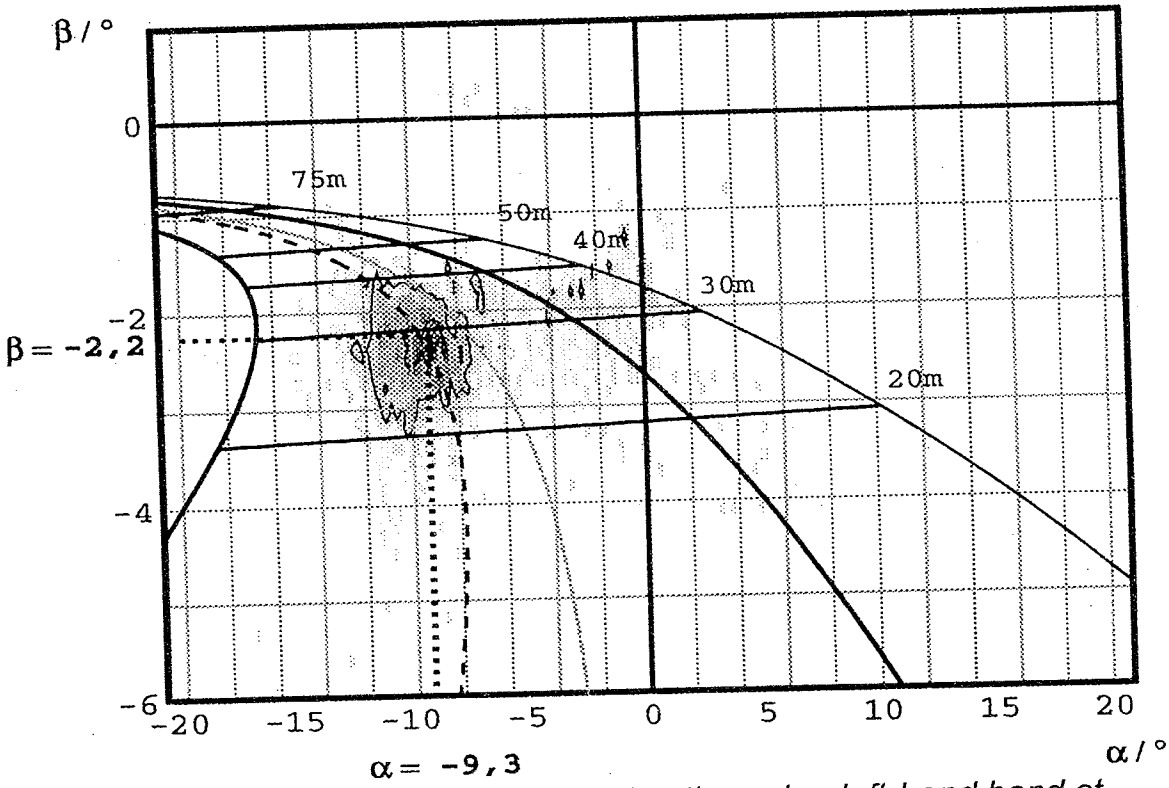

Figure 12: One fixation area when driving through a left-hand bend at night with GDL.
Headlamp system: gas discharge low beam (GDL)
Bend radius r = 110 m
Fixation direction: α = -9.3° β = -2.2°
FDAP: d = 30.9 m
Area factor: A_{f50} = 0.34

When measuring eye movement behaviour with GDLs in use, an increase of the fixation distance could be recognized. The FAP in left-hand bends is at the middle road marking (see Figure 12) and in right-hand bends at the right road marking (see Figure 13). FAP in both cases is on the bend tangent. It is important to notice that with GDL the driver has only one FAP, with HFL the driver has two FAPs.

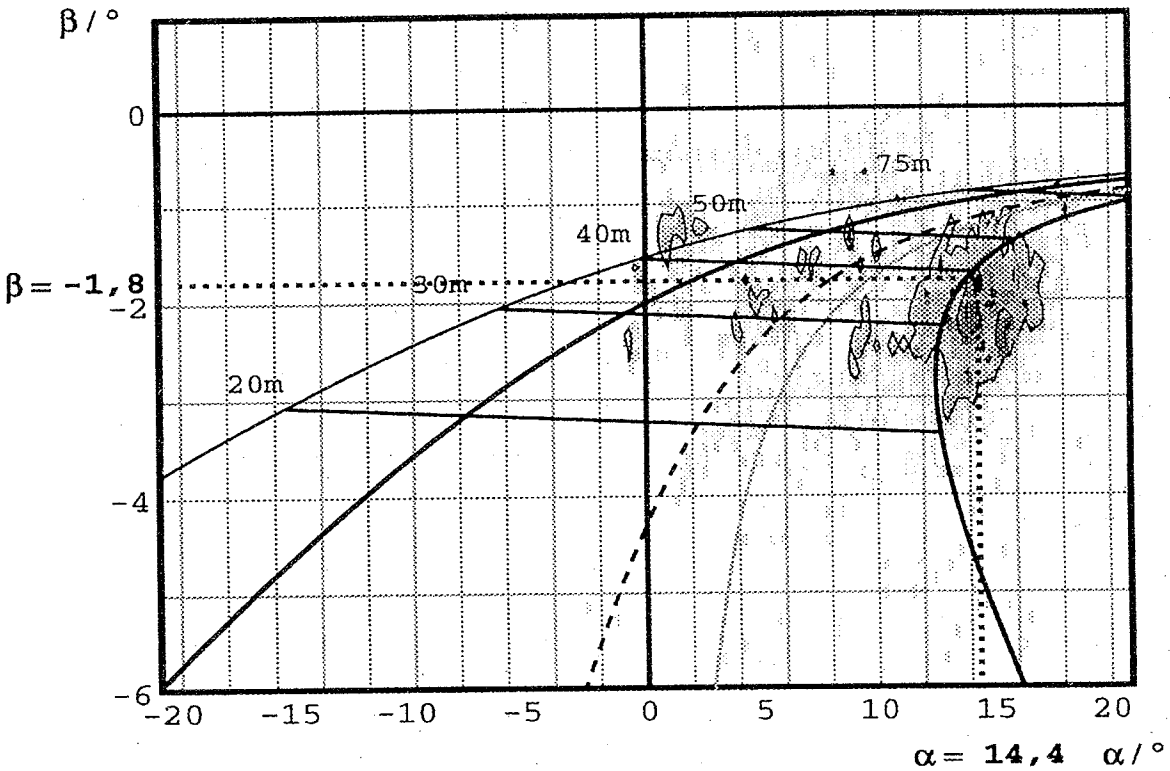

Figure 13: One fixation area when driving through a right-hand bend at night with GDL.
Headlamp system: gas discharge low beam (GDL)
Bend radius r = 110 m
Fixation direction: α = 14.4° β = -1.8°
FDAP: d = 38.5 m
Area factor: A_{f50} = 0.55

4.3 Night-time - Moveable Headlamps

The light distribution of the headlamps used here is identical for driving with and without moveable headlamps on straight roads. Hence it is unnecessary to show eye-movement behaviour on straight roads by using moveable headlamps again.

4.3.1 Moveable Halogen Headlamps at Night

Using moveable HFLs the fixations concentrate to the middle marking of the road and to the right-hand border of the road (see Figure 14 and Figure 15). There is only one FAP instead of the two FAPs measured with standard HFL.

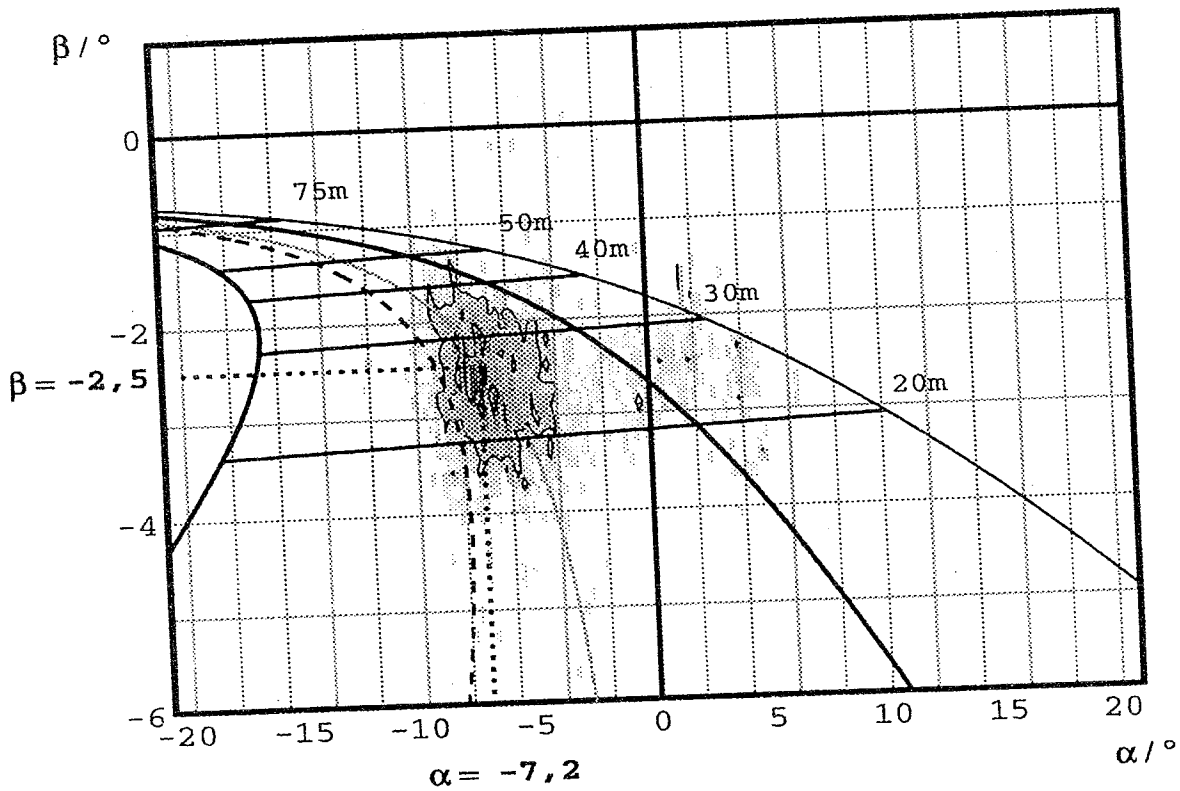

Figure 14: One fixation area when driving through a left-hand bend at night with moveable HFL.

Headlamp system:	*moveable HFL*	
Bend radius	*r = 110 m*	
Fixation direction:	*α = -7.2°*	*β = -2.5°*
FDAP:	*d = 27 m*	
Area factor:	*A_{f50} = 0.47*	

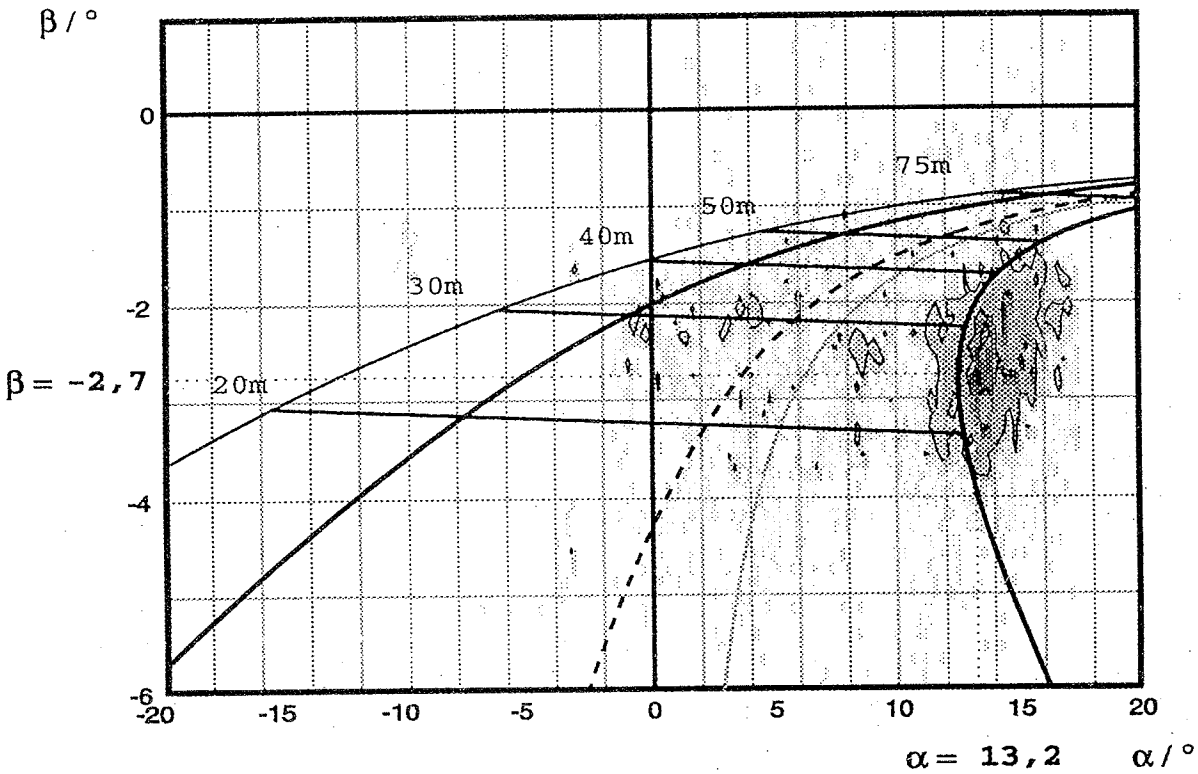

Figure 15: One fixation area when driving through a right-hand bend at night with moveable HFL.
Headlamp system: moveable HFL
Bend radius r = 110 m
Fixation direction: α = 13.3° β = -2.7°
FDAP: d = 25.5 m
Area factor: A_{f50} = 0.81

4.3.2 Moveable Gas Discharge Headlamps at Night

When using moveable GDLs the fixation distance accumulation point (FDAP) proved to increase to d = 35.8 m for the left-hand bends and to d = 43.5 m for right-hand bends. The distance values are slightly larger than the belonging daylight values (see Figure 16 and Figure 17).

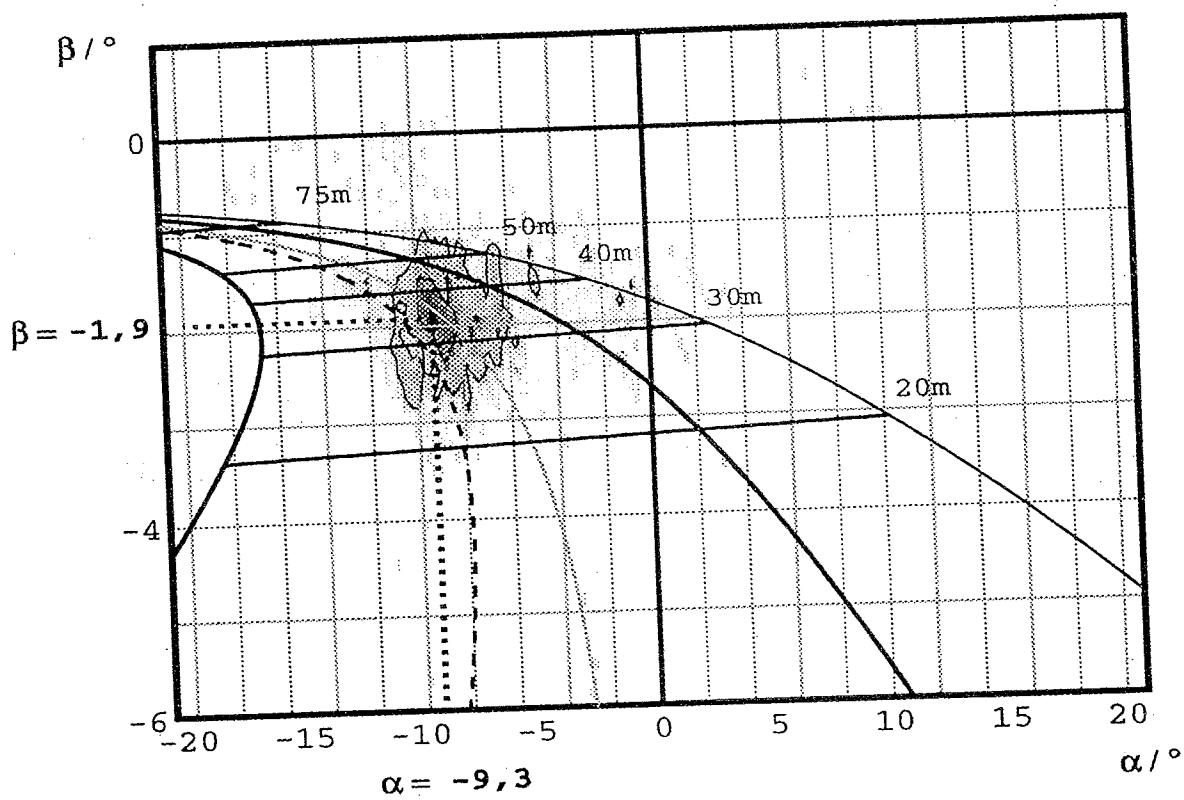

Figure 16: One fixation area when driving through a left-hand bend at night with moveable GDLs.
Headlamp system: moveable gas discharge (GDL)
Bend radius r = 110 m
Fixation direction: α = -9.3° β = -1.9°
FDAP: d = 35.8 m
Area factor: A_{f50} = 0.41

In the analysis of the right-hand bend (see Figure 17), it is noticeable that the spread of the fixations (field of interest) increases again. One explanation could be that because of the available luminous flux in direction of driving, the driver has the ability to recognize the subsequent direction peripherally and can fixate other interesting objects in the road area. With other words the driver has more time for driving and the tiredness of the eyes could be reduced.

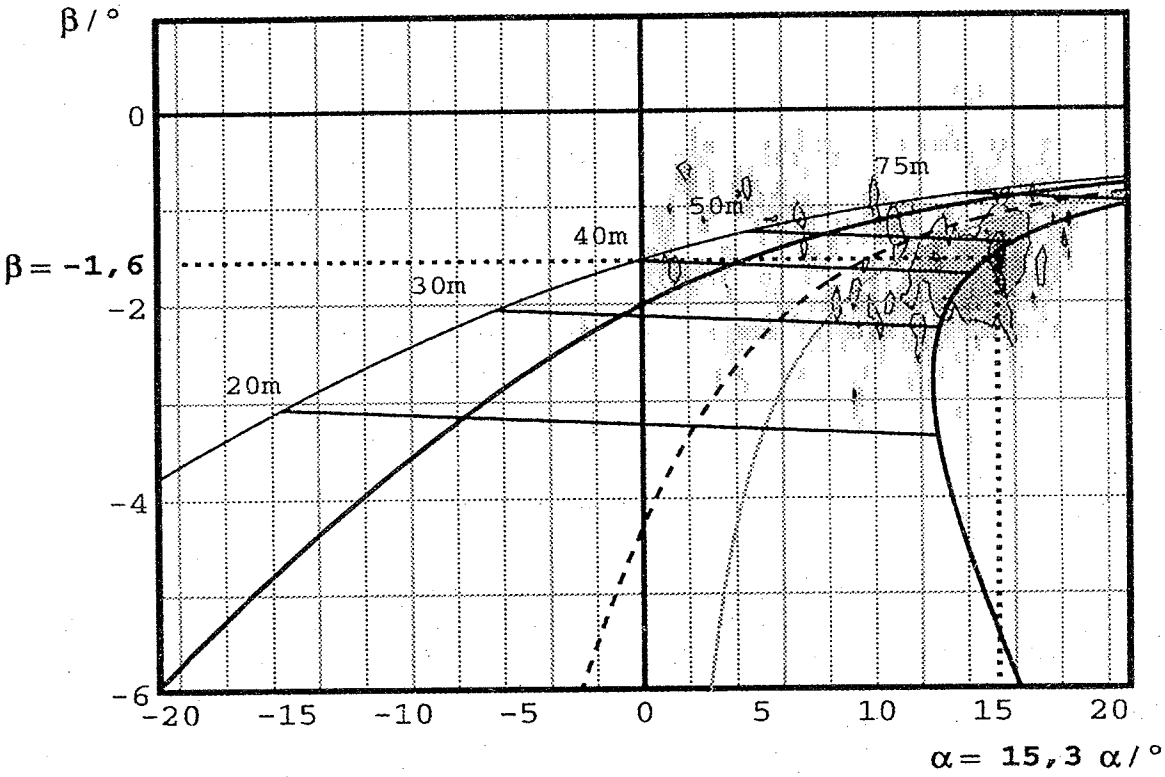

Figure 17: One fixation area when driving through a right-hand bend at night with moveable GDLs.
Headlamp system: moveable gas discharge (GDL)
Bend radius r = 110 m
Fixation direction: α = 15.3° β = -1.6°
FDAP: d = 43.5 m
Area factor: A_{f50} = 0.53

5. Results and Conclusion

5.1 Results

In Table 1 and Figure 18 we compare the fixation distance accumulation points (FDAP). When driving with standard halogen filament lamps (HFL) there have been measured two fixation accumulation points (FAP), when driving with moveable HFLs this was reduced to only one FAP, which could also be noticed with standard gas discharge headlamps (GDLs).

The FAP is more distant when using moveable GDL compared to driving at day light (especially in right-hand bends). As is generally known the light distribution of GDLs illuminates farther than the HFLs. Therefore larger fixation distances are possible. By using moveable headlamps (HFL+GDL) the illumination is remarkable larger in driving direction when passing bends.

		fixation behaviour											
		daylight				night-time							
	light source					standard headlamp				moveable headlamp			
road / bend		α/°	β/°	d/m	A_{f50}/1	α/°	β/°	d/m	A_{f50}/1	α/°	β/°	d/m	A_{f50}/1
straight	HFL	2.2	-0.7	95.8	0.10	2.4	-1.4	47.9	0.14	2.4	-1.4	47.9	0.14
straight	GDL	2.2	-0.7	95.8	0.10	0.0	-1.0	67	0.22	0.0	-1.0	67	0.22
left	HFL	-14.1	-2.0	34.6	0.81	-11.9	-2.9	23.6	0.88	-7.2	-2.5	27	0.47
left	GDL	-14.1	-2.0	34.6	0.81	-9.3	-2.2	30.9	0.34	-9.3	-1.9	35.8	0.41
right	HFL	13.0	-1.8	38.2	0.71	-12.3	-2.7	25.4	0.64	13.3	-2.7	25.5	0.81
right	GDL	13.0	-1.8	38.2	0.71	14.4	-2.8	38.5	0.55	15.3	-1.6	43.5	0.53

Table 1: Results of the fixation behaviour of the Figure 4 to Figure 17
HFL: Halogen filament lamp
GDL: Gas discharge lamp

Important is to point out that moveable HFLs do not achieve a FDAP as distant as the FDAP of non-moveable GDLs. Also, observable is that the FDAP using moveable GDLs is larger than the FDAP when driving at daylight. This could be explained as follows: When driving at daylight the driver could use the peripheral vision and could acquire necessary information about the road geometry ahead using few fixations in a distance of 50-100 meters for bends. For the lane keeping in bend itself the drivers use fixations in a shorter range of about 35 meters (1-2 seconds ahead). But, when driving at night the driver has no information about the scenery ahead and, also, can use peripheral vision only very limited. The necessary information for orientation must be acquired

by foveal vision, i.e. using fixations. Therefore, by having the ability to fixate much farther with moveable GDLs the driver actually uses this to achieve information about the scenery ahead with fixations in a range of about 35-45 meter. To summarize, the FDAP during driving at daylight seems to be representative for fixations for lane keeping while the FDAP during night-time driving seems to be the main fixation point for orientation.

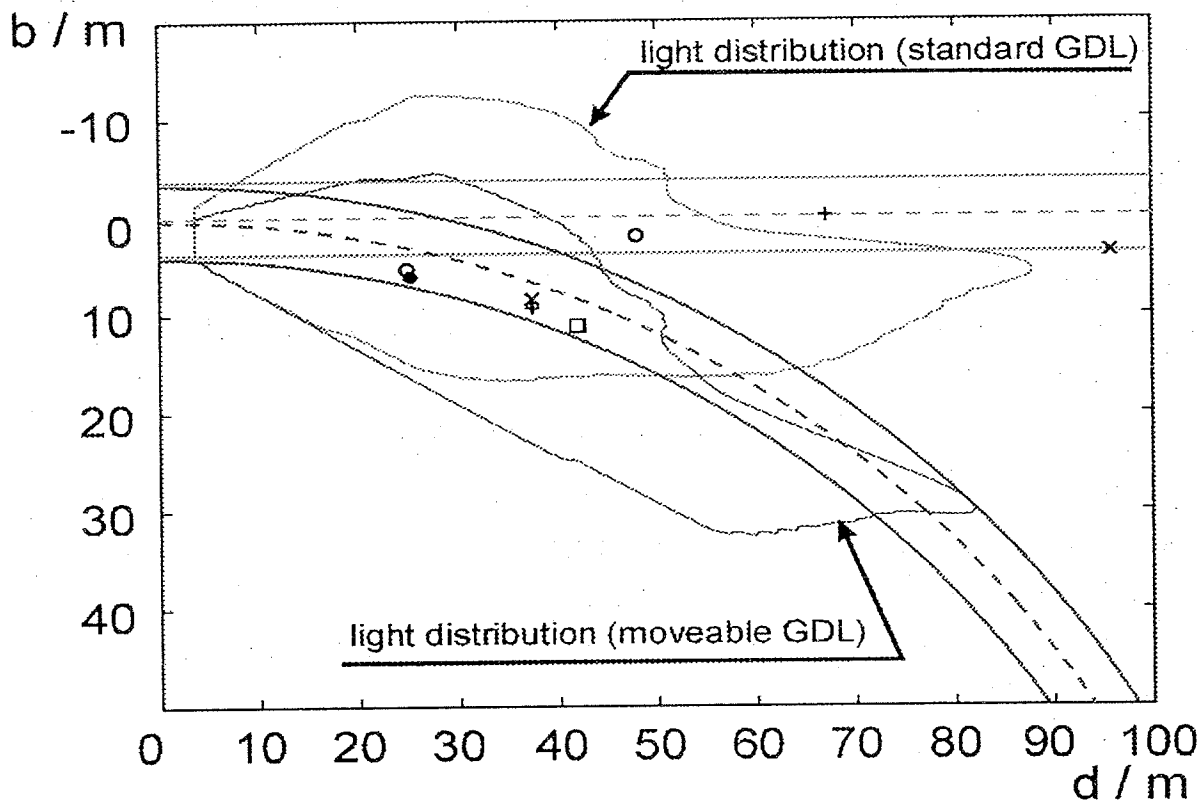

Figure 18: Fixation distance accumulation points (FDAP) for different headlamp systems and different road parts.
Accumulation points: X: *daylight*
O: *standard halogen*
●: *moveable halogen*
+: *standard gas discharge*
□: *moveable gas discharge*

5.2 Conclusion

In this paper experiments concerning the analysis of the eye-movement behaviour for 4 different headlamps conditions are presented. First results with moveable headlamps show clearly the advantage of moveable GDLs over static GDLs as well as over moveable HFLs.

In addition, the use of moveable GDLs shows no negative effect on driving behaviour. The experiments demonstrated the subjective advantage of moveable GDLs for the driver. The moveable GDLs seem to serve as an active guidance device for the driver by means of lighting up the scenery primarily in driving direction.

In the near future the focus will be on experiments concerning the characterization of FDAPs at daylight and night-time driving with different dynamic light patterns for moveable GDLs.

6. Literature

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