Advanced Vehicle Navigation applied in the BMW Real Time Light Simulation

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Advanced vehicle navigation based on the US Global Positioning Systems (GPS) will play a major role in future vehicle control systems. Contemporary vehicle navigation systems generally consist of vehicle positioning using satellites and location and orientation of the vehicle with respect to the roadway geometry using a digitised map on a CD-ROM. The standard GPS (with Selective Availability) enables positioning with an accuracy of at least 100 m and is sufficiently accurate for most route guidance tasks. More accurate, precision navigation can be obtained by Differential GPS techniques. A new light concept called Adaptive Light Control (ALC) has been developed with the aim to improve night-time traffic safety. ALC improves the headlamp illumination by means of continuous adaptation of the headlamps according to the current driving situation and current environment. In order to ensure rapid prototyping and early testing, the step from offline to online (real-time) simulation of light distributions has been successfully completed in the driving simulator. The solutions are directly ported to real vehicles to allow further testing with natural road conditions.

KEY WORDS

1. Road Vehicles. 2. Light Control. 3. Automation.

1. INTRODUCTION. Contemporary vehicle navigation systems generally consist of vehicle positioning using satellites and location and orientation of the vehicle with respect to the roadway geometry using a digitised map on a CD-ROM. A large potential for driver assistance in the future can be derived from the use of data provided by the navigation system. Using the course of the road, future vehicle systems will be able to think ahead and assist the driver. An example of such driver assistance is the development of Adaptive Light Control (ALC). ALC is a new light concept with the aim to improve night-time traffic safety. Due to the difficulty and costs of developing appropriate automotive headlamps, a driving simulator has been used to allow rapid prototyping. To enable the interactive development of new light distributions in different driving situations and driving environments, it was necessary to implement a real-time light simulation.

2. GLOBAL POSITIONING SYSTEMS. The development of the Global Positioning System (GPS) was initiated in the early 1960s by several US government organizations including NASA and the DOD. Presently, GPS is fully operational and

meets all the criteria established in the 1960s. The system provides accurate, continuous, worldwide, 3-dimensional position and velocity to users based on a normal constellation of 24 satellites.[1] GPS utilises the concept of one-way time-to-arrival ranging enabling the receiver to determine the satellite-to-user range. At least four satellites are required to determine user latitude, longitude, height and receiver clock offset for internal time.

2.1. *Differential GPS*. Differential GPS (DGPS) enhances stand-alone GPS accuracy and removes common (i.e. correlated) errors from two or more receivers viewing the same satellites. The differential positioning mode requires a ground reference station that is surveyed in a precisely known geodetic position. Because the monitoring station knows its precise position, it can determine the errors in the measured satellite ranges. For real-time applications, the reference receiver transmits these biases, called differential corrections, to all users (often called rovers) in the coverage area. The user can incorporate these corrections to improve the accuracy of their position solution. Some positioning errors are spatially correlated. This means that position solutions for users further away from the reference receiver will be less accurate than those closer to the monitoring station. DGPS techniques that utilize phase information of the GPS satellite carrier frequency require more base stations than code-based differential techniques. Local area DGPS might extend up to 400 km or more whereas carrier phase DGPS generally require base stations that are no further than 15–75 km away from the user. With wide area augmentation in conjunction with code-based differential GPS, a small number of reference receivers could cover an area as large as the United States. Its principle is based on estimating the errors of each component for the entire region, rather than only at the station positions.

2.2. *Inertial Navigation Systems* (*INS*). GPS receivers can be thought of as discrete-time position/velocity sensors with typical sampling intervals of 0·2–1 sec. There is a clear need to provide continuous navigation during periods of shading of the GPS receiver's antenna, and through periods of interference. The solution is integration of GPS with various other sensors of which the most popular are inertial sensors (typically measuring yaw rate and acceleration). The method most widely used for integration is Kalman filtering. Inertial navigation can therefore be seen as a 'flywheel' to provide positioning during shading outages. However, employing GPS and INS is a synergistic relationship: the GPS sensor can calibrate the INS sensor when its accuracy degrades over time, and the INS can support the GPS if satellites are obscured for a limited amount of time due to overhead obstructions such as bridges or trees.

The quality of INS very much depends on the quality of the inertial sensor used. With medium fidelity, mid-range priced yaw rate sensors in combination with the wheel-speed signals used by the ABS system, the position of a vehicle can be propagated up to 30 sec with an error of less than 1 m. The most significant factor related to the quality of an inertial system is the drift of a yaw rate sensor. Manufacturing a gyroscope with low drift is very costly. Accuracy of less than 0·01 degree/hour is available at prices from \$10000 to \$100000.

2.3. *GPS ACCURACY*. The standard GPS currently available for civil applications enables positioning with an accuracy of at least 33 m (1 σ error) without Selective Availability (S/A), and 100 m with S/A, both are sufficiently accurate for most route guidance tasks.

Code-based differential techniques allow an accuracy of 3 m whereas carrier-based techniques, using the GPS satellite signal carrier frequency, may result in centimetric accuracy. Figure 1 gives an overview of expected accuracies. The main sources for inaccuracies are: satellite clock error, ephemeris prediction error, Selective Availability, atmospheric effects, ionospheric effects and tropospheric delays. The single largest error source is Selective Availability (SA). SA is intentionally induced by the US DOD to degrade the user's navigation solution and was implemented in 1990. The degradation is mainly accomplished through dithering of the satellite clock resulting in a time-varying disturbance of the range.

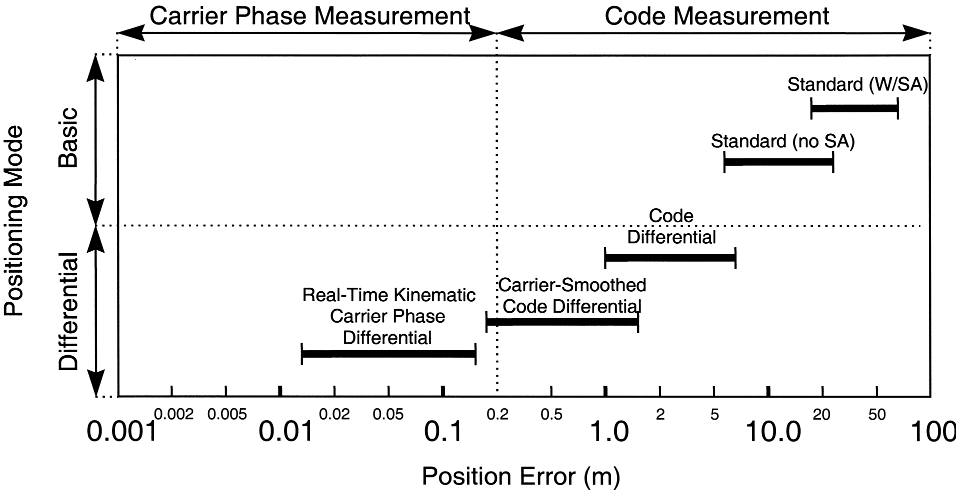

Figure 1. GPS positioning accuracy.[2]

3. MAP DATABASES. As well as the determination of the vehicle position using GPS, another viable source of information for advanced vehicle navigation is required: the road map. Knowledge of current position combined with the geometry and attributes (for example, the number of lanes and traffic signs) of the road in the immediate area of the vehicle enables the driver to extend his/her visual horizon to an electronic horizon with a much larger range. Currently available map databases are mainly intended for in-vehicle route guidance and are mostly available on a CD-ROM. A majority of these digital road maps have been digitised by means of a very labour intensive process using detailed topographic maps and aerial photographs. The accuracy is determined by the resolution of the base map and photo material and by the person operating the digitiser, and amounts on average to about 15 metres. Up-to-the minute cartographic material is crucial in providing viable, efficient navigation functions. According to the map compilers, 10–25 percent of the road segments will undergo changes every year. Therefore, updates of the map database for route guidance applications are made available to the end user on a quarterly basis. These (semi-static) digital road databases are excellent for turn-by-turn and door-to-door navigation. However, many of the future driver assistance applications need high fidelity positioning (which is now becoming available) and precise up-to-

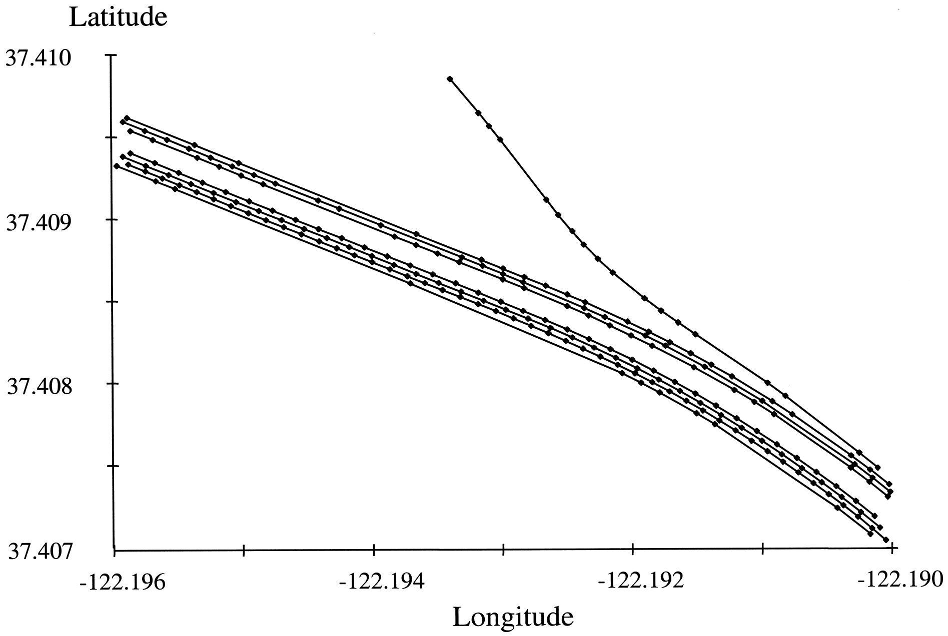

Figure 2. Example of RTK-GPS position on Hwy. 280 while driving on each lane a single time.[3]

date digital maps. The precision of these maps needs to be in compliance with the position accuracy of the GPS/INS system. There is a clear need for refined road geometry databases in the near future. While some desired extensions, such as the inclusion of the position and type of traffic signs in the database can be added quite easily, others additions might be much harder to achieve. It is very unlikely that manual digitisation of cartographic maps and aerial photos can be undertaken cost-effectively when high-precision road databases are required. Therefore, new techniques need to be developed to digitise and code the roadway geometry. The concept of using 'vehicles as a probe' might lead to the solution. The probe principle assumes that each vehicle can relay its position back to a central database server. The data collected by numbers of vehicles over many trips can be combined in such a manner that an accurate roadway geometry description can be compiled. This principle has some major advantages:

(i) high accuracy (cm level with RTK (Real Time Kinematic)-GPS),
(ii) the accuracy increases with time (multiple runs over the same stretch),
(iii) fast update (lane diversions due to road works can be recognised quickly by correlating data of many probes),
(iv) data sharing among probes: obtain accurate geometry information recorded by other probes for previously 'unknown' areas,
(v) ability to combine the system with telematic servers (as well as position, vehicle speed, outside temperature, road friction condition, visibility, etc. can be transmitted to the server and shared with other road users)

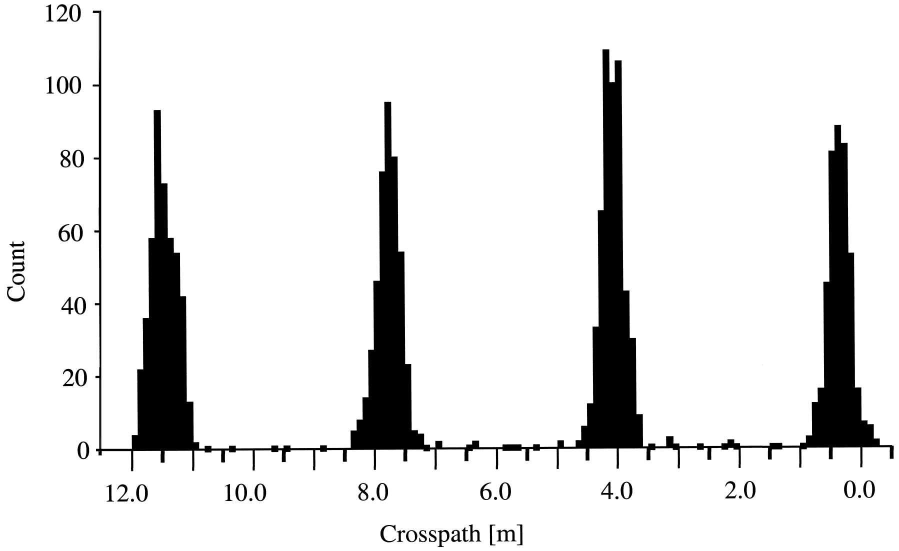

Figure 3. Distribution of RTK-GPS position across the total width of a four-lane highway.

Some of the concerns are:

(i) the map database reflects the real driving behaviour (people cutting off corners, for example),
(ii) dedicated two-way data links required for differential corrections and actual data transfer,
(iii) massive amount of data to be processed at the central server,
(iv) penetration (a minimum number of probe vehicles is necessary),
(v) privacy issues: system can be used for policing or commercial exploitation
(vi) high fidelity GPS receivers are still very costly.

Figure 2 shows an example of how well the geometry of a typical highway can be digitised using a probe vehicle equipped with a carrier phase DGPS system able to determine its position with cm accuracy. Each lane on a four-lane highway has been driven once with a BMW probe vehicle.

Figure 3 provides a distribution of lateral vehicle position over the entire width of the road while driving for 1 mile in each lane. The lane positions can be clearly discriminated and most of the positioning variations are due to the deviations in lane keeping behaviour of the driver.

BMW believes that building a road geometry database using probe vehicles will not replace the currently available navigation databases. It will be very unlikely that traffic sign recognition, geocoding and traffic rule abstraction can be handled by probe vehicles owned by regular customers. Therefore highly accurate (dynamic) databases will coexist in parallel to (static) route guidance databases.

4. DRIVER ASSISTANCE APPLICATIONS.

The concept of driver assistance systems has been a major focal point of the research at BMW[4]. Driver assistance systems are aimed at reducing high workloads on the driver and mitigating the consequences of specific driver deficiencies. BMW does not pursue the vision of automated vehicle control. Despite all the technical possibilities available, the driver-active car will remain the focus of development efforts in the future. Therefore, the following premises are of great importance:

- The driver must have the freedom to decide, if and when she/he wants to use the assistance system.
- The assistance system explains its behaviour and provides feedback to the driver in an easily understandable manner.
- The assistance system behaves smoothly and should not affect the dynamics of driving (when needed).
- The driver can always override the assistance system.
- For almost every driver assistance system, it is of great importance to have information about the traffic and driving situation with a certain preview. A so-called electronic horizon informs or reacts in advance to events that either are outside of a driver's visual range or whose continuous monitoring would pose an unnecessary burden. The electronic horizon can be derived from sensory information, from telecommunication and from the positioning system (GPS) in connection with digital road maps.[5]

The spectrum of applications for information about vehicle positioning and the characterization of the road is almost unlimited. Figure 4 provides an overview of various driver assistance systems in combination with different levels of available GPS accuracy, a detailed description of all the systems in Figure 4 can be found elsewhere.[4,5] Safety critical applications, such as lane keeping support and collision avoidance, require much more accurate vehicle positioning (and map database) than comfort orientated applications like turn-by-turn navigation. Even with today's

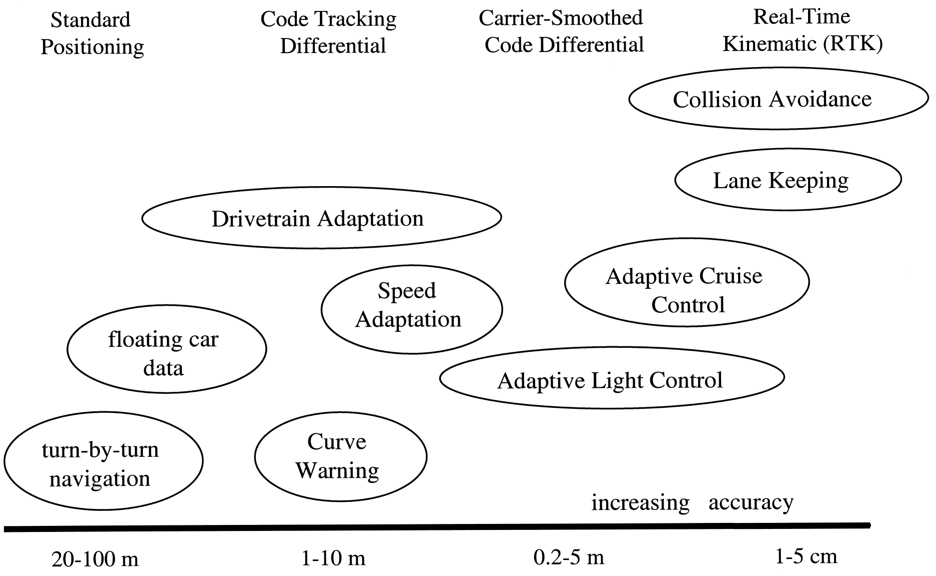

Figure 4. Driver assistance systems and GPS accuracy.

accuracy of the GPS system and map databases, applications like, for example, the range management of electrically powered vehicles could be realised. Driver assistance systems with GPS integration will most likely be introduced in different generations, where the first generation will be based on standard (differential) positioning in conjunction with currently available navigation databases. Later generations with more functionality will use more accurate receivers and need better maps with a higher accuracy and more attributes. The following sections, outline the interactive environment for developing new lighting systems using real-time simulation of light distributions in the driving simulator for the a driver assistance application, called Adaptive Light Control. This incorporates driving dynamics, GPS and map databases of different levels of fidelity.

5. INTERACTIVE ENVIRONMENT FOR NEW LIGHTING SYSTEMS.

Normally, a headlamp is first designed and then its characteristics are tested and optimised for practical use. Due to the difficulty and costs of developing appropriate automotive headlamps, a lot of work has been done on light simulation. Usually, static light distributions for specific situations have been modelled in an offline simulation, with a CPU-time from 10 seconds up to minutes per frame[6,7]. A real-time simulation of (dynamic) light distributions did not exist, and hence, a tool to evaluate light distributions adapted to different driving situations or influenced by different weather conditions has not been available.

By combining high-performance computers and specially developed lighting software with a real-time kernel, an environment is produced that allows online simulation of light distributions and, therefore, interactive development of lighting systems. The simulation produces a series of images (30–60 frames/second) that is projected onto a screen and enables interactive driving in the simulator with modelled light distributions (see Figure 5).

Figure 5. Real-time light simulation in the driving simulator.

5.1. *Driving Simulator*. The core of the driving simulator is an Onyx2 IR2 Silicon Graphics system operating in conjunction with specially developed lighting software. It enables the animation of the driving environment with stable 60 Hz in a 190 degree front view and three rear views covering the mirrors of a car. The Onyx is equipped with 12 CPUs (R10k, 250 MHz) and three Infinite Reality2 Pipes with 6 raster managers. Several graphical databases are implemented including textures for trees, buildings, signs, and cars[8]. A wide range of simulation modules enables the realisation and verification of automotive solutions like driver assistance systems and vehicle concepts with appropriate man-machine interfaces.

To test different light distributions, a specially designed light course was developed. The driving simulator contains a closed course with many different curves and includes a crossing. The radius of curvature of the bends varies between 25 and 150 m. The width of the road is 7 m with a centerline and beacons every 50 m. Decorated with buildings, bushes, trees, pedestrians and traffic signs, it provides a very realistic appearance.

5.2. *Online Manipulation of Light Distributions*. The light distribution is simulated not only in real time but is also changeable online and can be checked immediately. Figure 6 shows the shape of cut-off illumination of the road integrated with the lighting software in the driving simulation. Figure 7 shows the isolux diagram at road level for the same distribution. With these light distributions, as an example, the following issues can be addressed:

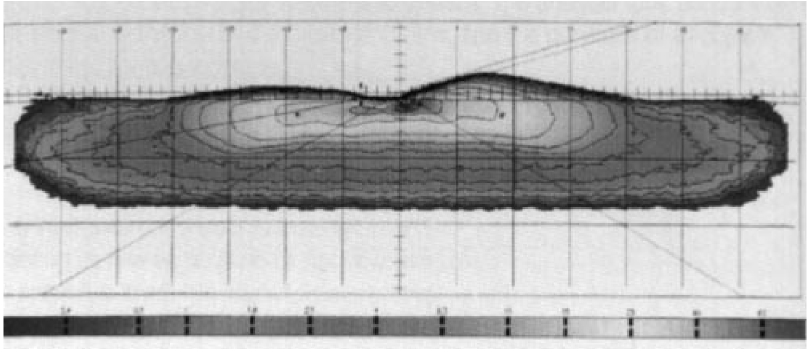

Figure 6. Integrated light distribution in the driving simulator.[9]

- Cut-off line simulation,
- Dynamic headlamp levelling,
- Evaluation of light distributions (different light distributions),
- Change of the distribution (for example, low beam and low beam with spot),
- Bending light with curve illumination.

6. ADAPTIVE LIGHT CONTROL (ALC).

Adaptive Light Control is based on the ability to adapt the headlamps dynamically by means of moveable reflectors, according to the current driving situation and environment.[10] These headlamps can be controlled using the vehicle trajectory prediction based on vehicle dynamics and/or route vectors from the navigation system.

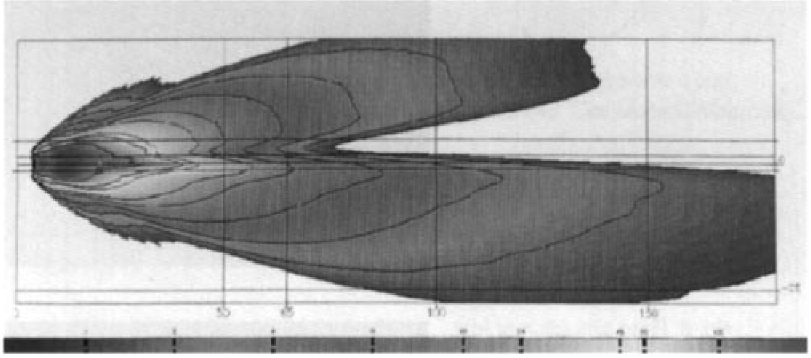

Figure 7. Isolux diagram at road level.

Figure 8. Conventional headlamp system.

In the latter case, the GPS system consistently tracks the precise location of the vehicle and, with its built-in digital road map, has knowledge of the road characteristics ahead.

The advantage of using Adaptive Light Control is shown in Figure 9, when compared with conventional headlamps in Figure 8. The vehicle is approaching a bend on a secondary single lane road at night. It can be clearly seen, that with the ALC system, the turn is much better illuminated enhancing the visual information for the driver. While the vehicle is still on the straight part of the road, the headlamps are already directed into the turn. This is clearly an advantage of using GPS in combination with a navigation road database. This feature could not have been realised using, for example, a fixed ratio between steering wheel angle and headlamp orientation or a dynamic relationship based on vehicle dynamics. In the early development phase of the ALC system, the BMW driving simulator was used successfully for development, validation and optimisation purposes.[11]

6.1. *Dynamic Light Simulation with Standard GPS.* By combining high-performance computers and specially tuned lighting software, a tool has been

Figure 9. Adaptive Light Control.

developed to simulate and to evaluate light distributions adapted to different driving situations, road or weather conditions. In order to use the navigation system in the driving simulation, the output data has been simulated with the standard GPS accuracy in a manner reflecting the characteristics known by the real system. The information is limited to 2D geographic data without height information. To achieve realistic results, the GPS and map data are simulated with distortion and noise (low fidelity data) and are included in the overall solution. A special protocol was used to provide the following information:

1. current vehicle position,
2. route data vectors of the scheduled route, with:
   - (a) reliability of the route data vector,
   - (b) current road class,
   - (c) on-map or off-map status.

This navigation data together with online driving dynamics have been used to control the moveable reflectors in the headlamp. Experiments in the driving simulator and tests with real vehicles with the standard GPS accuracy have shown that the vehicle dynamics-based path prediction and the two-dimensional navigation data used to control the headlamps is limited to a certain road geometry. When encountering hilly roads, s-curves and other types of special roads, standard GPS and map databases are not accurate enough. Additional knowledge is necessary to overcome these deficiencies. This has led to the simulation and use of highly accurate DGPS and more appropriate road databases.

6.2. *Dynamic Light Simulation with DGPS and* 3*D Database*. In addition to the vehicle dynamic parameters, route vectors from the navigation system with differential techniques with a three-dimensional database were used to control the headlights. A real existing course was chosen as a test bench. The ALC system is provided with three-dimensional location of the longitude, latitude and altitude and with the current position of the vehicle. The driving dynamic status of the car is coupled with the DGPS data via a point filtering (Kalman-filter) and bi-splines to derive the shape of the road.

Figure 10. ALC controlled by standard GPS on a hilly and curvy road in the driving simulation.

As shown in Figure 10, adjustable lights controlled by standard GPS in the driving simulation did not work in hilly environments with tight turns. The road could not be illuminated well enough due to insufficient accuracy of the road database in combination with the standard GPS accuracy. In comparison, Figure 11 demonstrates very nicely that the moveable reflectors controlled by high accuracy differential GPS in combination with a 3D road database illuminates the curve in a useful manner.

Figure 11. ALC controlled by high precision GPS in combination with the road database on a hilly and curvy road in the driving simulation.

7. CONCLUSION. Driver assistance systems rely heavily on remote sensing for road traffic situation perception. The concept of advanced vehicle navigation extends the driver's visual horizon to an electronic horizon with a much larger range. The ability to combine dynamic data (such as vehicle and object position/velocity

recorded by a laser/radar/vision sensor) and static data (such as the roadway geometry from a vehicle navigation system) provides the means for a driver assistance system to generate a *clear* picture of the current road scene.

It was shown in various real-world experiments that the integration of advanced vehicle navigation in driver assistance systems can achieve substantial benefits in terms of reliability, robustness, increased functionality, fuel efficiency as well as active safety. Driver assistance products using map databases as an additional source of information will most likely be introduced in phases. First generation products may be based on currently available GPS technologies and might use map databases designed for route guidance applications. Second generation applications will be based on higher levels of the accuracy of GPS and map databases.

Using special graphic algorithms, an advanced vehicle navigation with a real-time light simulation with 30–60 frames/second has been achieved. According to this real-time simulation, a dynamic bending light has been developed for Adaptive Light Control (ALC). The solution of ALC with control algorithms and lighting strategies has been realised first in the driving simulator. It has been ported with minimal effort to real vehicles where prototypes of ALC are now under investigation. First tests demonstrated the subjective advantage of ALC for the driver; it seems to serve as an active guidance device by lighting up the scenery primarily in the driving direction, especially in curves.

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