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7–9 May 2012, Dubrovnik, Croatia

# Road and Rail Infrastructure II

**Stjepan Lakušić – EDITOR**

Organizer
University of Zagreb
Faculty of Civil Engineering
Department of Transportation

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EDITOR
Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

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# VIRTUAL ROAD MODELS FROM DYNAMIC MEASUREMENTS

**Kai Tejkl, Wolfram Ressel**
*University of Stuttgart, Institute for Road and Transport Science,*
*Chair for Road Design and Construction, Germany*

## Abstract

For modelling real road characteristics in a driving simulator, a measuring vehicle and an algorithm to generate virtual road models from recorded data were developed. Especially properties which affect driving dynamics and comfort are of great interest. Therefore a standard passenger car was equipped with several instruments to detect the road geometry and the longitudinal profile for describing surface characteristics. After a measurement run, the processing of measurement data is performed offline with a purpose–made software that semi–automatically creates road models in the formats OpenDRIVE® and OpenCRG®, which are widely–used in driving simulators. Therefore several independent steps are necessary.

Preliminarily a node–edge model of the investigated road network is established. An algorithm which allows an automated parameter calculation for the standard road alignment elements straight, arc and cubic polynomials, based on the measured, discrete GPS–waypoints was developed with regard to a realistic modelling. This reference line can be amended afterwards by further cross–sectional properties. For this purpose the software visualizes data from a laser scanner. Finally all roads are merged to a network by adding a logical linkage.

In the next step, a three–dimensional surface model for each road section is created from longitudinal profiles. The result is stored as an OpenCRG®–model, a 'Curved Regular Grid' where each cell contains discrete height information. In combination with the OpenDRIVE® roads this yields to a visual and haptic road description for the driving simulator.

This work was carried out as part of the research project VALIDATE (Virtual Automotive Lab for Integrated Digital Automation Technologies) at the University of Stuttgart leading by the Institute for Internal Combustion Engines and Automotive Engineering with the partners High Performance Computing Centre Stuttgart and the Institute for Road and Transport Science, funded by the German Federal Ministry of Education and Research (BMBF).

*Keywords: alignment, surface, road survey, driving simulator*

## 1 Introduction

The development of new systems in automotive engineering requires always risky and costly tests under real conditions. To reduce these disadvantages the project VALIDATE [1] had the aim to create a research platform to investigate future control and assistance systems in a virtual environment. Therefore one of the biggest driving simulators in Europe was constructed. Within this framework the creation of virtual road models was object of investigation at the Institute for Road and Transport Science. In contrast to the fictitious roads, which are commonly used in driving simulators, this research had the aim to model a real road network including the characteristics of roads, which influence driving dynamics, driving resistance and driving comfort in order to provide a realistic driving experience.

The research consisted of two parts, the design and construction of a measuring vehicle to record the relevant road characteristics and the development of algorithms to process these data into an appropriate road description. This article gives an overview about the main steps as shown in Figure 1.

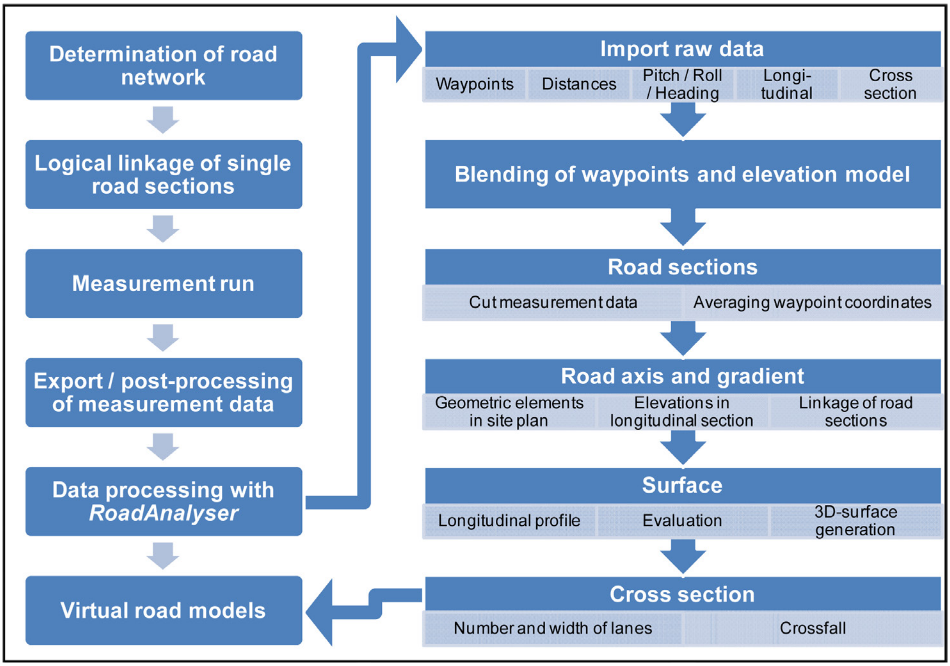

**Figure 1** Workflow for creating virtual road models

## 2 Road measurements

Basis of the virtual road models are measurements of the investigated road network carried out dynamically. Therefore a standard passenger car was equipped with different measuring instruments, which amongst others record GPS–waypoints, heading–, pitch– and roll–angle, longitudinal and cross–sectional profile. A data acquisition unit [2] synchronously stores all signals with a time stamp in a single data file and guarantees a consistent data set of all properties. The different measurement instruments mounted at the vehicle are shown in Figure 2. A combined inertial measurement unit (IMU) and GPS–receiver [3] records GPS–waypoints as well as all vehicle motions in three spatial directions in real–time. An additional optical sensor [4] allows a more precise navigation by slip–free measurement of velocity. For the measurement of the longitudinal profile a profilometer as described in [5] consisting of four triangulation laser sensors [6] is used. As the profilometer is mounted flexible, the longitudinal profile can be recorded either in the left or right wheel track. So the resulting road surface can be described by two independent tracks. Crossfall and lane width are determined using a laser scanner [7] at the rear of the vehicle in combination with data from IMU. The scanner measures the distance to the road surface crossways in driving direction over 180 degrees. Two video cameras on the roof additionally record every measurement run.

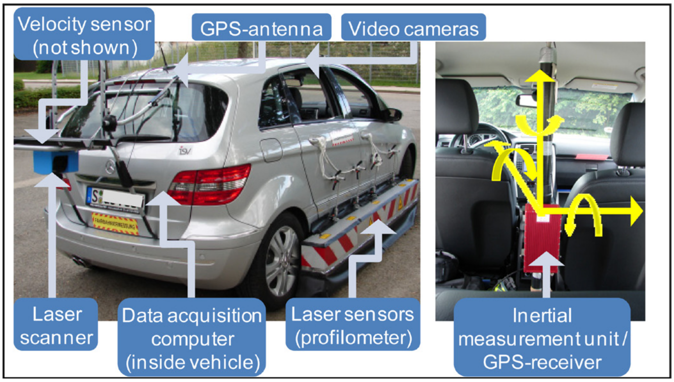

**Figure 2** Measurement vehicle at Institute for Road and Transport Science

## 3 Target data formats

For later visualisation and driving dynamics simulation a common data format for the description of the investigated road network and the road characteristics is necessary. As they are already widely–used the open formats OpenDRIVE® [8] and OpenCRG® [9] were chosen.
The open XML–format OpenDRIVE® allows a hierarchical description of all road characteristics. Within a road network single road sections corresponding to the node–edge model in section 4 are determined. These are linked by their unique ID. A particular role is given to junction areas as the roads inside this area allow a lane–specific connection of each incoming and outgoing road. The geometry of each road section is initially described by a reference line (the road axis) in the site plan, consisting of the geometric elements straight, arc, spirals or polynomials with reference to an absolute x/y–coordinate system. Along the reference line a relative s/t–track–coordinate system is introduced as basis for all further descriptions like the elevation profile, lane width or positions of signs and signals.
Additionally to the OpenDRIVE®–format the OpenCRG®–format describes the three–dimensional surface characteristics. Basic principle of OpenCRG® is a two–dimensional regular grid along the predefined reference line in longitudinal and cross direction. A discrete height–value in z–direction is defined for each cell thus results in a three–dimensional surface. The resolution of the grid can be chosen arbitrarily. However, small excitations won't influence the driving comfort.

## 4 Preparation of road network

The investigated road network has firstly to be determined and transferred into a node–edge model with unique ID's where all junctions are divided into several sub–nodes and the edges represent single road sections between them. An example of the dissolved junction ID = 1 is shown in Figure 3: The sub–nodes 1E, 1W and 1N are defined on the road axis of each access to the junction. Incoming and outgoing roads ID = 1, 2 and 3 to the adjacent junctions are then treated as free road sections. Every possible connection between the sub–nodes is finally described by six separate connecting roads ID = 11 to 16.
As almost every junction has own characteristics – especially complex junction areas like interchanges with a lot of sub–nodes – this preparatory step can only be carried out manually with the help of aerial photographs. This concerns also the second preparation step: the logical linkage of all roads and junctions by their ID according to the OpenDrive® specifications. However it's possible to define standard junction types as the linkage e.g. inside a T–junction is always the same.

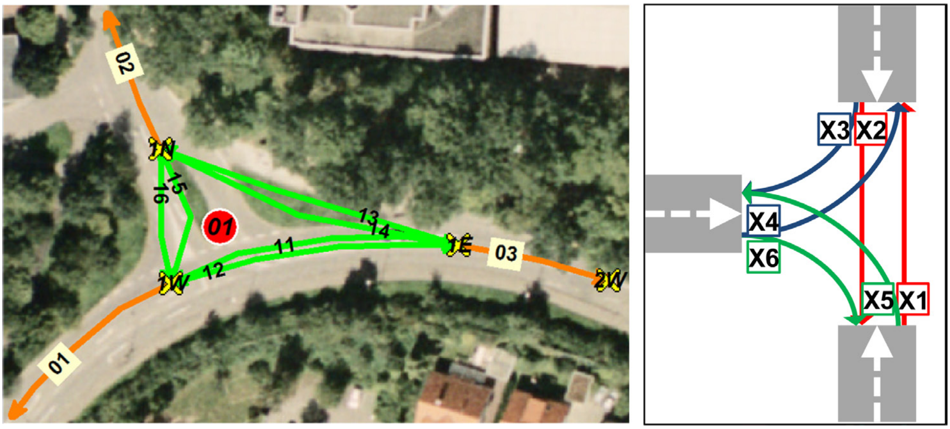

**Figure 3** Example of node–edge model in junction area and standard linkage of a T–junction (Source aerial photograph: LGL Baden Wuerttemberg)

## 5 Road geometry

Main target of the research was the development of an algorithm which generates the virtual road models according to the formats described in section 3 based on the raw data of a measurement run. It was implemented as a MATLAB–Toolbox with the main steps shown in Figure 1.

As described in section 3 the road axis represented by the reference line is essential for all further characteristics like number of lanes, lane width, crossfall and surface. However, the measurement data contain only discrete waypoints. So the continuous reference line described by mathematical functions has to be approximated. On the contrary to other methods which use cubic spline–curves the developed algorithm calculates the geometric standard elements straight, arc and transition curves.

The data preparation initially contains a coordinate transformation into a local metric system. All measurement data of the whole road network are then cut into single sections according to the predefined node–edge model. If a road section was recorded more than one time (along both driving directions), the waypoints of each lane can be averaged to identify the central road axis. Basis for the determination of straights and arcs is the road heading along the track coordinate s (Figure 4). The heading gradient allows their identification as it can be interpreted as the antiderivative of the curvature. Therefore statistical values of the heading gradient are stepwise calculated. While these values are within a predefined tolerance, constant or linear segments are recognized. Between the known start and end point of each element further parameters (radius, length etc.) can then be calculated.

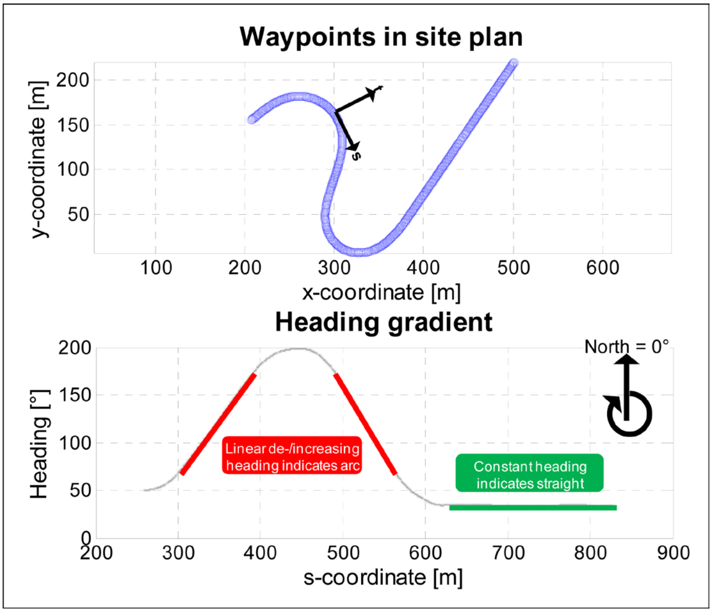

**Figure 4** Determination of arcs and straights in heading gradient calculated from waypoints in site plan.

Finally transition curves are fitted between the straight and circular elements (Figure 5). For this purpose 3rd grade polynomials described by Eq. 1 are used. The coefficients a, b, c and d of a polynomial element i are calculated from the boundary conditions derived from the end point of the preceding (i-1) and the start point of the following (i+1) element (Eq. 2 and 3).

$$y = a + bx + cx^2 + dx^3 \tag{1}$$

$$f(x_{i-1,end}) = f(x_{i,start}) \text{and} f'(x_{i-1,end}) = f'(x_{i,start}) \tag{2}$$

$$f(x_{i+1,start}) = f(x_{i,end}) \text{and} f'(x_{i-1,start}) = f'(x_{i,end}) \tag{3}$$

All calculated parameters of straights, arcs and transition curves describing the continuous road axis are then stored in the OpenDRIVE®–format and further road characteristics can be attached to this reference line.

The gradient in the longitudinal section is calculated in the same way as described above. However, the elevation profile is used instead of the heading gradient and only continuous defined 3rd grade polynomials are assumed.

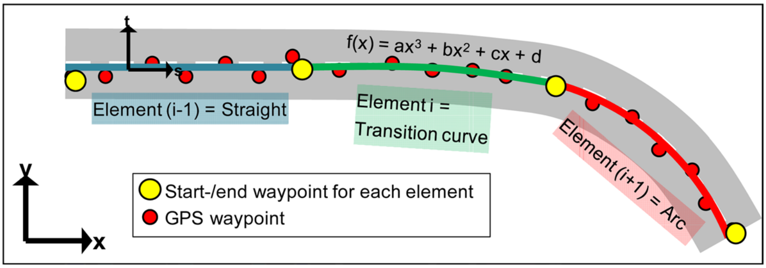

**Figure 5** Calculation of transition curve between straight and arc.

# 6 Road surface

The road surface consists firstly of the 'flat' lanes along the previously defined reference line. It is then superimposed by the regular elevation grid.

## 6.1 Lanes

The width of each manually predefined lane can be calculated from the measurement data of the laser scanner. These contain also information about the reflectivity of a laser beam, so light/dark boundaries as they result from the marking along a road can be identified (Figure 6). The abscissa in the diagram of reflectivity specifies the positive s–coordinate along the road axis and the algorithm searches for the first light/dark boundary in positive and negative t-direction which represents the road marking left and right of the vehicle in driving direction. The lane width at each s–coordinate can then be calculated as the absolute difference of the filtered and interpolated t–coordinates and will be described by an approximated 3rd grade polynomial as a function of s.

Furthermore the crossfall and superelevation of each lane can also be defined. For this purpose, the data from the laser scanner in combination with the synchronous measured roll angle of the vehicle is used.

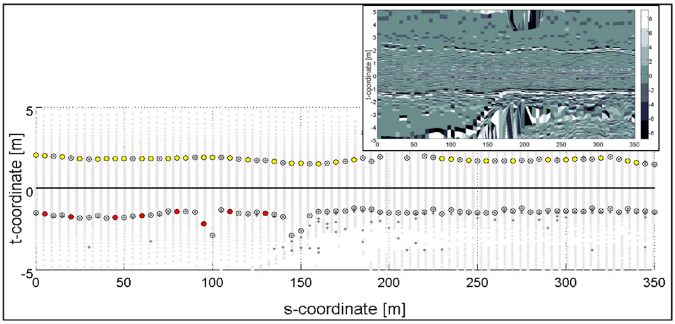

**Figure 6** Diagram of reflectivity along the road axis and approximated interpolation points along the lane edge.

## 6.2 Longitudinal unevenness

With regard to a realistic driving experience in the simulator the road models contain also longitudinal unevenness as wave lengths between 50 cm and 50 m, which are mainly responsible for driving comfort [10]. As described in section 2 the longitudinal profiles are measured in both wheel tracks. This especially respects different vehicle excitations [11]. The profile contains all relevant wave lengths and describes the height of the road surface with 10 cm resolution relative to a fictitious base line. Additionally the longitudinal unevenness is evaluated based on the power spectral density at a frequency of $\Omega_0 = 1/m$ according to German rules for road surveys [12].

The process of generating a three–dimensional surface is shown in Figure 7. The corresponding profile heights between the two longitudinal profiles are interpolated over the wheel gauge respectively extruded to the edge of the lane. According to the arbitrarily chosen resolution of the elevation grid the heights are then discretised and stored for each cell in the OpenCRG®–format.

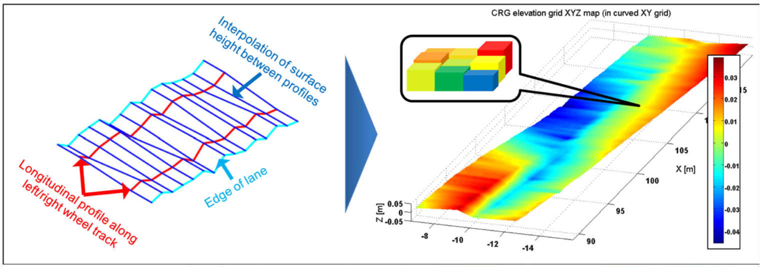

**Figure 7** Interpolated profiles along left and right wheel track and resulting three–dimensional surface model with discrete heights of each cell.

## 7 Conclusions

This article gives an overview about the process to convert data from real road measurements into a virtual road model. Based on this a complete road network can be described including road geometry, cross–sectional properties and surface properties. The road models can be used for visualisation as well as driving dynamics simulation and were already successfully tested in a driving simulator. Furthermore the principle of the developed virtual road models also allows implementation of more detailed properties like short–wave texture.

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