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Digital Terrain Models for Road Design and Traffic Simulation

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ABSTRACT

This paper presents some of requirements traffic engineers currently impose on digital terrain models from a practical point of view.The alignment of new road infrastructure must be carefully planned due to increased requirements of the Environmental Impact Analysis imposed by the European Union. Public authorities. Geometric design of roads by itself follows national standards and an engineering process including linear alignment, road cross sections and adjacent roadside environment. Calculations of the horizontal and vertical road centerline determine the three-dimensional physical location of a road considering operational, economic and environmental requirements. The geometric design of a road includes all visible features of a road notwithstanding whether it is an urban, rural or interurban road. Powerful Computer Aided Design (CAD) software enhances the ability of an engineer to conduct numerous design iterations and presentations suitable for public hearings. The digital database for project scenarios are typically based on digital terrain models (DTM) with two-dimensional grids and the perpendicular height as third dimension (z-value). The cell length of the grid and the accuracy of the z-value are relevant for the quality of the geometric design. Feasibility studies with alternative alignments require less accuracy of the height (10-20 cm) than detailed operational studies (1 cm). 3D-animation features of CAD software require the same accuracy in order to provide jerk-free movements of vehicles along the designed road. Traffic flow simulation is not only used for animation purposes but also for calculations of road capacity, fuel consumption and emissions. A method to compute energy consumption based on road alignments with height accuracy of 2-5 cm will finish up this paper.

1. GEOMETRIC DESIGN OF ROADS

1.1. Roads must fulfill different objectives imposed by traffic flow requirements, traffic safety regulations and environmental constraints. Design engineers must propose options with a suitable balance between these three objectives while taking into account the construction and maintenance cost for the public agency being responsible for the road. According to Directive 2011/92/EU of the European Parliament all projects of newly built four or more lnae roads must pass an intensive Environmental Impact Analysis (EIA). This also includes new alignments of existing roads of more than 10 km length. Less important roads may not require an EIA but still must be built according to geometrical design standards. Roads are typically classified in three main categories: motorways with grade-separated intersections, highways outside of built-up areas and urban roads. A considerable variation of national and regional design standards exist which define number of lanes, lane width, shoulder, slopes curvature, superelevation of curves, vertical curves and sight distances. The design elements are influenced by a wide variety of design controls, engineering criteria and project specific objectives (Wright and Dixon, 2004) such as

- traffic safety considerations;
- functional classification of the road;
- type of intersections;
- forcasted traffic volumes and level of truck usage;
- anticipated vehicle size and weight;
- topography, earth quality of the surrounding landscape and possible geotechnical treatment;
- public involvement and environmental considerations.

Most countries agreed upon national or regional road design standards. Some typical design standards are listed in Table 1. These standards are recommended practices for all roads, except national roads,

Editor	Guideline	Title (engl)
Austrian Asscociation for Research on Road-Rail-Transport (FSV)	RVS 03.03.23	Road alignment
	RVS 03.03.31	Cross sections of non-urban roads
	RVS 03.04.12	Cross sections of urban roads
German Road and Transportation Research Association (FGSV)	RAST 2006	Design of urban roads
	RAL 2012	Design of trunk roads (highways)
	RAA 2008	Design of motorways
Design Manual for Roads and Bridges (DMRB) by the UK Department for Transport (DfT)	TD 9/93	Highway link design
	TD 27/05	Cross sections and head rooms
	TD 22/06	Layout of grade seperated junctions

Table 1: Typical national standards on geometric road design in Austria, Germany and UK.

which require a more strict approach to the guidelines. Some countries organize the guidelines by road type while others classify by link (longitudinal), cross sections (lateral) and junctions.

1.2. The use of computers and Computer Aided Design software (CAD) revolutionized highway design in the early 90´s. Standardized digital data formats have allowed engineers to exchange projects at different planning levels. Horizontal alignments, cross sections profiles and quantities on earth movements can be produced for numerous scenarios at fairly little extra amount of work once the initial planning stage has been computerized. Many companies provide CAD software for road design purposes. The most prominent CAD software worldwide for road design are AutoCAD (Autodesk) and OpenRoads (Bentley Systems Inc.). However, such general CAD software is usually not configured to support regional guidelines as in table 1. Therefore several companies provide either proprietary software or add-on libraries for the above CAD software to match regional standards. In German speaking countries CARD/1 (IB&T) and VESTRA (AKG) are the most widely used software packages for road design. The drawings of this paper are prepared using VESTRA 7.

Geometric road design is usually based on digital terrain models available from the national agencies for cartography and geodesy. Typically grid surface data DEM (digital elevation model) is available with equally spaced squares and the grid cell value representing the elevation at the centroid of each cell (Maune, 2007). The grid spacing and accuracy of the elevation value readily available by the national agencies is usually sufficient for general alignment studies.

Before a road is actually built a more accurate conventional terrestrial field survey is conducted within the vicinity of the construction site. The following table identifies the accuracy of the grid data which is available by public agencies.

Agency	Item	Accuracy
Austria: Bundesamt für Eich- und Vermessungswesen www.bev.gv.at	Grid width	10 m
	Height accuracy	±1 m to ± 3 m (urban areas, farmland)
	Height accuracy	±10 m to ± 25 m (forest, alpine region)
Germany: Bundesamt für Kartographie und Geodäsie www.bkg.bund.de	Grid width	10 m
	Positional accuracy	±0,5 m to ±3 m
	Height accuracy	±0,5 m to ±2 m
Switzerland: Swisstopo www.swisstopo.ch	Grid width	2 m
	Position and Height	±0,5 m to ±1 m below 2000 m altidude
	Position and Height	±1 m to ±3 m above 2000 m altidude
Aerial photography undertaken in Styria, Austria and used for the following examples	Grid width	1 m
	Position	±40 cm
	Height	±10 cm

Table 2: Highest accuracy of ready available DTM´s as gridded surface.

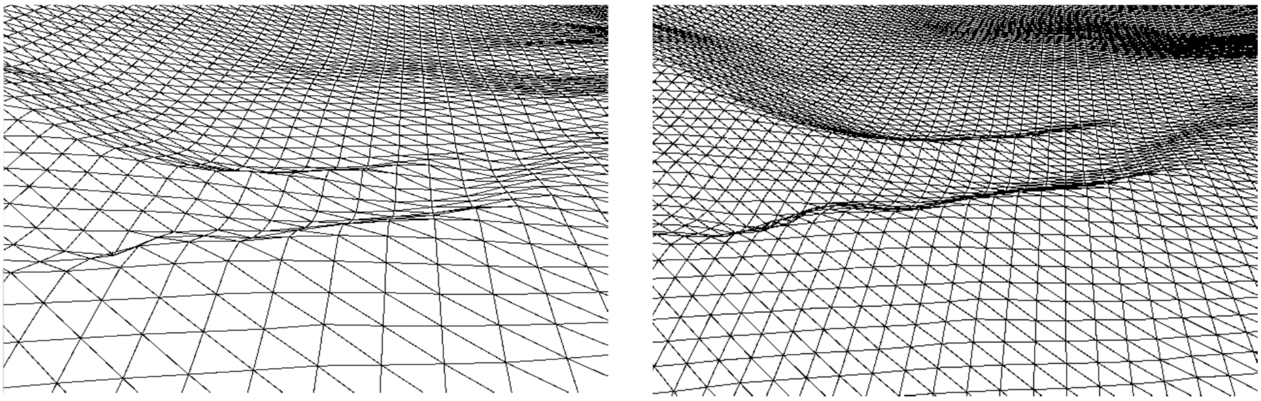

Figure 1: Triangulated irregular network in hilly terrain based on 2 m (left) and 1 m grid (right); same viewpoint as in Fig. 4a with front only.

1.3. In road design DTM (digital terrain models) are used not considering the surface of trees, foliage and housing. The grid information is used by the numerous CAD software to generate a triangulated irregular network (TIN) by interpolation between various cell centroids. Besides different deterministic interpolation methods such as inverse distance, spline or natural neighbor, geostatistical interpolation technique known as kriging is sometimes used to create a good representation of the terrain with a reasonable number of well distributed data location points. Figure 1 depicts the same area with two different resolutions of initial grids.

	Data points		**TIN**	
Cell size of Grid	**# cells**	**storage [MB]**	**# triangles**	**storage [MB]**
1	2.860.000	80	5.715.600	268
2	715.000	16	1.427.800	67
5	114.400	3	227.900	10,7
5 (10 cm reduction)			196.600	9,9

Table 3: Size of TIN for 2,2*1,3 km rectangle in Styria.

The minimum cell width is not only a matter of the available resolution of the raw data but also constrained by the hardware available at the computer of the traffic engineer who is typically not equipped with a full featured GIS/CAD workstation. The example of this study includes a 2 km stretch of a two-lane trunk highway in hilly terrain. The rectangular grid of the terrain is 2,2 km by 1,3 km. The CAD software used provides a utility to eliminate triangles if the difference in elevation does not exceed a threshold value (e.g. 10 cm). Since the terrain is quite hilly in this examples this feature does not reduce the TIN significantly. While survey workstations can usually handle TIN´s with 268 MB, (= 1 m grid) regular CAD software and workstations for traffic engineers are suited to handle the 10 MB data (= 5 m grid). This resolution is sufficient for a first investigation on alternative alignments studies. In this example a new road shall be designed to connect point A and B with cuts in orange and embarkments in green (Fig. 2a). Traditionally the traffic engineer thinks and views his project in three angles; the horizontal alignment, the vertical alignment (Fig. 2b) and the cross section. The vertical alignment identifies points of vertical intersections at which the slope changes. On a detailed planning level the slopes can not change suddenly with discrete values but must change gradually according to a transition curve. Transition curves are needed for crests as well as sags, because of driving comfort and visibility. The standards differ how to compute the transitions curves with increasing curvatures at higher design speeds.

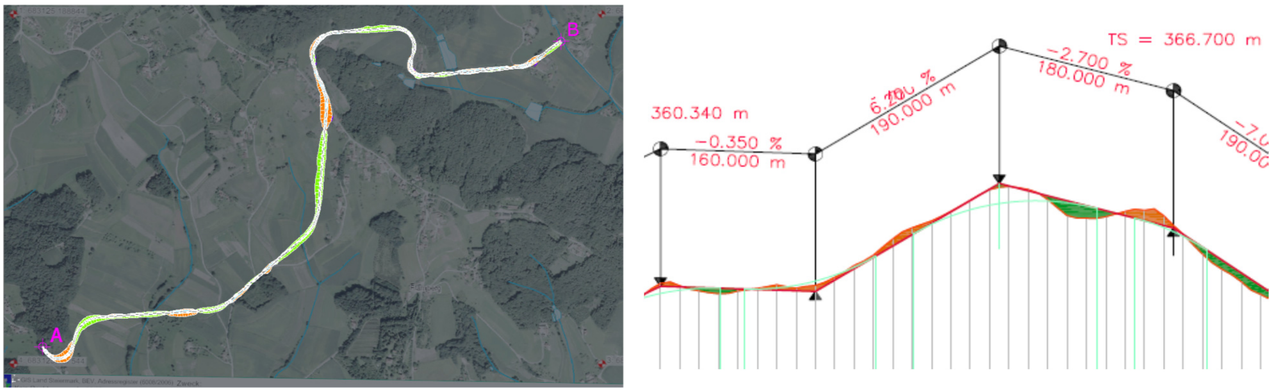

Figure 2: (a) horizontal alignment on orthophoto considering topography (b) vertical alignment.

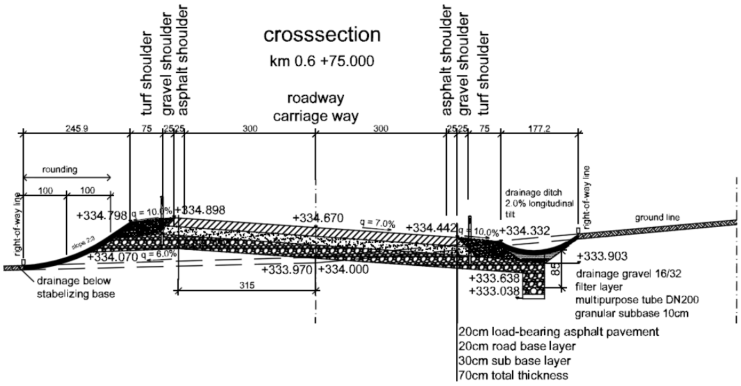

Figure 3: Cross section with cut and embarkement (left side).

In order to identify the best horizontal alignment, the height at cross sections is needed in 10 cm accuracy. Detailed planning is needed for final designs and construction which requires cross sections at every 10 m and height at 1 cm accuracy drawn in mm-units. Thus, for final designs we still require terrestrial surveying. Cross sections need to be at a higher level of detail since the drainage of the road has to be considered. For straight roads many standards require a minimum crossfall of 2,5% with a superelevation of up to 8% within curves (Fig. 3).

1.4. The traditional distinction between horizontal and vertical alignment with discrete cross sections is fading with the help of DTM´s and powerful 3-D CAD-software. New roads are designed and superimposed on the DTM. Required earthwork with cuts and embarkments can easily be seen on a continuous basis along the designed road (Fig. 4a). If cross sections are calculated continuously with interpolation between the profiles, the engineer may generate films (Fig. 4b).

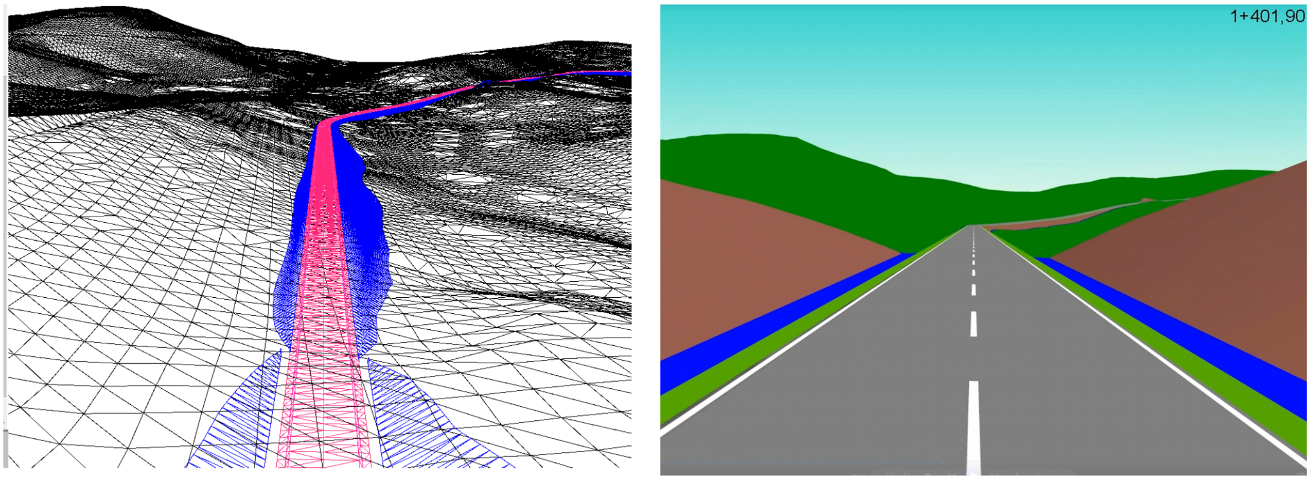

Figure 4: (a) geometrical design of two-lane highway superimposed on DTM with cut and ditch in the front and embarkement in the back and (b) same view visualized in 3D.

2. TRAFFIC FLOW SIMULATION

2.1. For traffic operation traffic engineers model traffic flow in order to acquire knowledge about the system behavior. Like in many other fields of engineering simulation has gained serious interest in research since 40 years and is widely accepted in practical application for the last two decades. For many studies different microscopic traffic flow simulators were developed in order to replicate traffic behavior on urban streets as well as motorways. Common applications include (Fellendorf and Vortisch, 2010):

- Corridor studies on heavily utilized motorways to identify system performance, bottlenecks and potentials of improvement.
- Motorway studies including control issues like contra-flow systems, variable speed limits, ramp metering, route guidance and operational impacts during phases of construction.
- Corridor studies on arterials with signalized and non-signalized intersections.
- Signal priority schemes for public transport within multimodal studies.
- Capacity of public transport lines with various types of vehicles such as Light Rail Transit (LRT), trams and buses with refinements in design and operational strategy.
- Investigations on traffic calming schemes including detailed studies on speeds during maneuvers with limited visibility.
- Impact of new vehicle technolgoy such as Car-to-Car or Car-to-Infrastructure communication on safety, capacity and overall system performance.

Most traffic flow simulators contain at least four different modules: (a) a block which models the network topology including road configuration, position of stop bars and stops of public transport (Fig. 5), (b) a vehicle block which defines technical features of the vehicle fleet, traffic volumes, and vehicle paths, (c) traffic control devices such as traffic lights which may respond on traffic volumes by adaptive green periods and (d) the model output such as performance figures on queue lengths, speeds etc. and 2 or 3D-animations (Fig. 6).

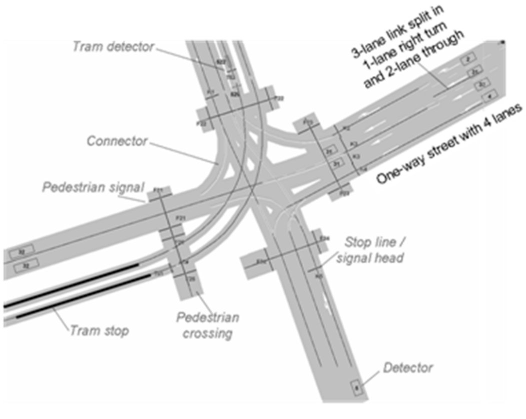

Figure 5: Urban signalized intersection with tram tracks as represented in microscopic traffic flow simulators.

Figure 6: 3D representation of a simulated urban intersection without rendering suited for traffic engineering purposes.

2.2. The kernel of any microscopic traffic flow simulator is the mathematical model of lateral and longitudinal movement. Vehicles – and in reality the drivers – respond to the neighborhood, which may be the road alignment, road signs, other vehicles and obstacles in general. Car-following as continuous process is usually sliced in discrete intervals of ms up to several seconds. The resolution depends on the level of detail to be modeled. To minimize computational effort but keeping the accuracy most simulators work with a resolution of 1 Hz to 5 Hz updating interval. Like any other simulator a traffic flow simulator must be as detailed to model the impact of planning differences which the engineer want to answer. This requires a minimum level of detail and a well calibrated model. Since traffic flow simulation contains traffic as a random Monte-Carlo process, different random seeds have to be considered to gain a stable average solution. This solution has to be calibrated against observations.

In the past only aggregate measures like cross-sectional traffic volumes and speeds were taken as reference quantities. Modern photogrammetric technology permits to compare measurements of single vehicle trajectories with simulated vehicles. Typically, single vehicles are equipped with high precision GPS. Vehicle positions are recorded at a rate of 100 to 5 Hz, supplemented by travel time measurements based on automatic number plate recognition. Calibration on a microscopic level allows evaluating parameters of single vehicle movements such as accelerations at each time step. Car following parameters and the distribution of desired acceleration can be adopted to match the measurements (Fig. 7).

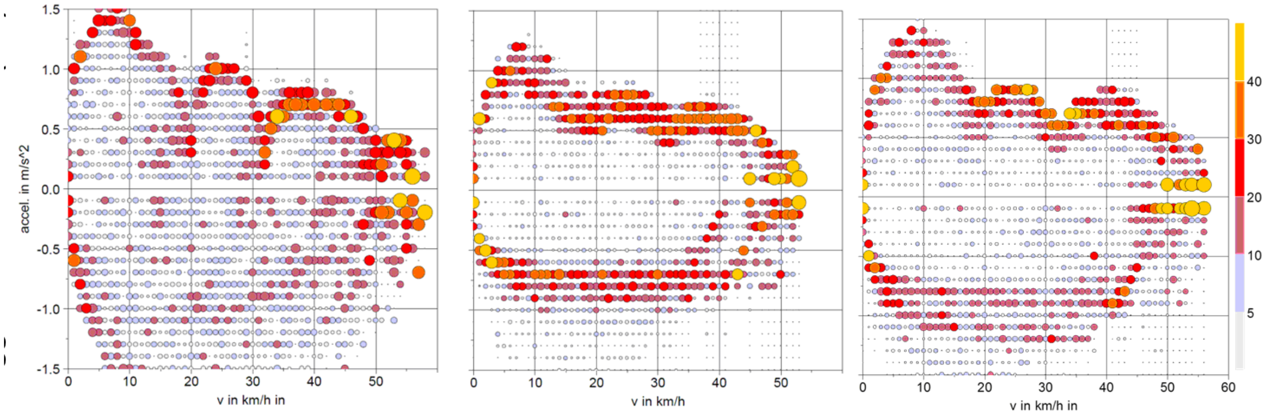

Figure 7: Measured and modeled acceleration rates over speed for a bus with hybrid engine (Kies et al., 2013).

2.3. Virtual Reality (VR) becomes relevant in traffic simulation to communicate design alternatives to public audiences and to support the decision making process. While standard quantitative measures of effectiveness, 2D output, and unrealistic 3D-images are sufficient to satisfy traffic engineering needs, the general public requires photo-realistic images due to the standards set by the movie and gaming industry. Large infrastructure projects in the Middle East and controversial traffic schemes like the ones during the Olympic Games in London 2012 require good communication of traffic management measures assisted by VR . The 3D-engines of traffic flow simulators do not meet the required quality, while standard VR-software does not model traffic flow by itself. The VR-designer has to define each single vehicle movement especially if vehicles decelerate due to cornering radius, traffic signals or vehicles with priority. Traffic flow simulation models the vehicle behavior without sufficient capability of realistic buildings and surrounding infrastructure. Research organizations and companies have linked the output of traffic flow simulators to 3D VR-software. Using a VR platform a highly realistic and accurate simulation of vehicles, pedestrians and traffic infrastructure such as road layouts, signals, street furniture and buildings can be achieved.

The microscopic traffic flow simulator provides vehicle position and type and signal states of traffic lights and variable message signs based on a given coordinate system. The 3D-engines takes this dynamic data, which either change position or state and merges this with static 3D information such as the road network, road markings, the terrain, trees, traffic lights and any other visible object, which should be considered to present a realistic image. After compiling static and dynamic 3D objects, the scene must be rendered to video SD or HD quality. Especially in hilly terrain the landscape must be modeled with great care of different height levels in order to provide jerk free movements of vehicles when going up and down as well as lane changes. This is also relevant when modeling grade-separated junctions with up- and downhill ramps (Fig. 8).

Figure 8: Simulated traffic flow on a grade separated intersection in photo-realistic quality © Sunovatech.

3. NEED OF ELEVATION FOR ENVIRONMENTAL MODELLING

Environmental Impact Analysis (EIA) plays an important role in planning and operation of roads. Quantitative values of traffic induced air pollutants are required to indentify suitable roadway options which help to meet emission standards. Microscale emission models such as PHEM (Hausberger, 2003) are linked to microscopic traffic flow simulation to compute vehicle emissions. For each sampled second the emissions are calculated taking vehicle type, speed and acceleration.

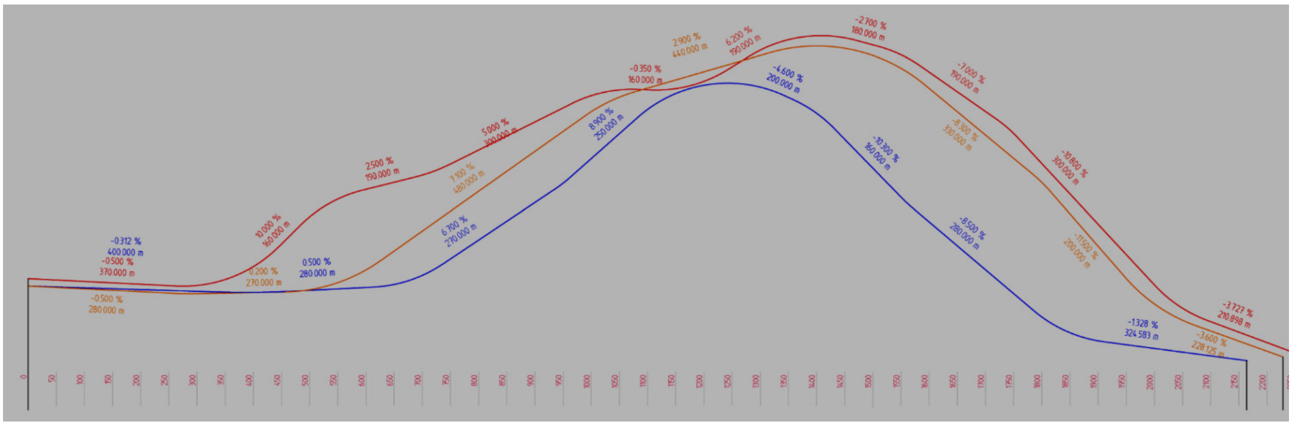

Figure 9: Vertical alignment of three alternative road designs.

For each vehicle type engine maps are available computing the emission by normalized engine power, torque and selected gear. The engine power itself is needed to overcome air, rolling, vehicle and gradient resistance to name the most prominent ones, Since the slope of a road has quite an impact on the power needed to move uphill, it has to be considered as shown in the following example. Let us assume three different alignment options for the above two lane highway with different elevations to be matered between point A and B as shown in the diagram of vertical alignments (Fig. 9). When calculating the three szenarios without considering the gradient, travelling on road design V1 is the fastest with minimum fuel consumption and emissions at V3. However, if gradient is considered the road design V2 will produce the minimum emissions because of the minimum elevation difference (Tab. 4). These results are site and vehicle fleet specific but demonstrate the influence of elevation in road design and emission.

road design szenario	**Fuel conspt** [g/Fz]	**NOx** [g/Fz]	**partiales** [g/Fz]	**Link length** [km]	**Travel time** [s]	**Total height** [m]	**Max slope** %
V1 w/o gradient	110,8	1,458	0,0318	2,2297	**99,7**		
V2 w/o gradient	100,4	1,142	0,0306	**2,1472**	104,3		
V3 w/o gradient	**99,1**	**1,127**	**0,0302**	2,2071	102,9		
V1 with gradient	115,3	1,571	0,0339	2,2301	**100,4**	45	10,8
V2 with gradient	**111,1**	**1,416**	**0,0333**	**2,1473**	104,6	37	10,3
V3 with gradient	112,1	1,429	0,0336	2,2074	103,6	44	11,5

Table 4: Emission values of Euro4 vehicle and geometric characteristics of three alternative road designs.

4. CONCLUSIONS

Geometric road designers benefit greatly from Digital Terrain Models. However the quality of the TIN´s and elevation grids provided by the national geodetic institutes should be improved. The current accuracy is sufficient for the pre-design state but not the final planning of roads. On the other hand the traffic engineers should learn the result and usage of new digital elevation model techniques which may arise from long range Light Detection And Ranging (LIDAR) and other emerging technologies. Furthermore, area-wide TIN´s or elevation grids with about 0,5 m accuracy of elevation are needed to improve macroscopic emission models as needed for future traffic management issues. New vehicle technology will be more sensitive on energy consumption which will require energy efficient route planning. Since road gradients are relevant to energy consumption, slopes will be embedded in digital road networks if area-wide elevation data is easily available.

GPS based trajectories provide an added-value to calibrate traffic flow simulation models. The accuracy should be improved but network-based real time kinematic (NRTK) GPS positioning as described in (Aponte etal 2009; Schenk, 2012) is not yet used in mobile vehicle trajectory recording.

5. ACKNOWLEDEGEMENTS

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