SYSTEM FOR INTERACTIVE 3D VEHICLE DYNAMICS ANALYSIS

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Abstract

The 3D vehicle dynamics simulation system combines the simulation model of a road vehicle and the display subsystem into a software application for scientific interactive driving simulation. The vehicle simulation model includes a fully parametric multibody-based model of driving dynamics that can simulate wheeled vehicles with four to eight wheels. Also included are mathematical models of powertrain elements, braking system and steering as well as models of interaction of vehicle with terrain and foreign objects. All the relevant parameters regarding the vehicle, the terrain and simulation system intrinsics, are accessible through graphical user interface. The terrain geometry can be imported from files in various formats and can be acquired from different sources. A separate software application has been developed for converting road surveying data to geometrical models of road sections for use in simulations. The results of simulations are presented in virtual 3D environment in real time. The user can navigate the virtual environment independently of simulated vehicle. The real-time input of vehicle control parameters is accomplished through a control device that can range from standard computer keyboards to real vehicle cockpit mock-ups. The simulation results can be exported as numerical data or digital video in real time. Part of the system is a library of 3D geometrical models of wheeled vehicles that can be used in various aspects of vehicle dynamics analysis. The entire system is used for preparing simulations, the results of which can be used for vehicle performance testing, vehicle – terrain interaction analysis, vehicle operator training etc.

Keywords: driving dynamics, vehicle simulation, virtual 3D display

Presenting Author's biography

Miha Ambrož is a researcher and Ph. D. student at the Department of Modelling in Engineering Sciences and Medicine, Faculty of Mechanical Engineering, University of Ljubljana. His main field of work is development of software for vehicle dynamics simulation and analysis.

1 Introduction

Traffic situation analysis by contemporary standards often requires results of analyses that can be performed only on computers with purpose-built software. An important part of this is vehicle driving dynamics simulation.

The requirements for vehicle dynamics computer simulations are very different and so are their implementations in software. Commercial tools exist for accomplishing many of the tasks related to this matter. Their functionality ranges from universal multibody system simulation environments (like MSC ADAMS [1]) to highly specialised tools for traffic accident analysis and reconstruction (like IbB CARAT [2] or DSD PC-Crash [3]). Among those tools are the simulators that can process the user input and display simulation results in real time and thus enable interactive driving simulation. These tools are very useful as trainers for vehicle operators and for various other aspects of traffic situation analyses. To achieve the required effect, these simulators have to run in real time, which is why they have to achieve a delicate balance between simulation accuracy and processing speed.

The result of the work presented in this paper is a software application for interactive driving simulation that is universal enough to allow simulations of the widest possible selection of wheeled vehicles (be it existing, modified or purely conceptual) on an arbitrary driving surface (either a measured existing terrain or artificially modelled). The benefit of such approach is a flexible application that can be expanded with new models of vehicles and terrains without having to significantly change the application itself. The application finds its use in various fields, which include vehicle testing and optimisation, driver training, terrain exploration, visibility analysis etc. The in-house development of the simulator application also means that it is possible to adapt its components to the current requirements and modify it to connect to other software and hardware applications (e.g. haptic interfaces for motion- and force-feedback).

2 Simulator design

To accurately simulate vehicle dynamics the simulator should include the model of vehicle dynamics, the model of vehicle powertrain and propulsion system, the model of braking system, the model of steering mechanism and the model of vehicle – terrain interaction. The individual parts of the simulator are described in detail in the following subchapters.

2.1 Multibody-based model of vehicle dynamics

The model of vehicle dynamics is multibody-based and modelled using the Open Dynamics Engine [4]. The vehicle is represented as a multibody system consisting of bodywork and four to eight wheels. The setup of a six-wheel vehicle is shown in Fig. 1. The wheels, together with suspension elements, are connected to the bodywork with double-hinge joints. The unsprung mass consists of wheel mass m_w and suspension elements mass m_s. Such a setup is largely consistent with the lumped mass model as described in [5] and [6]. Spring and damping characteristics of each wheel suspension are modelled by assigning the joint characteristics. Since the wheels are modelled as rigid bodies, the tyre spring and damping characteristics are computed separately and mechanically combined with suspension characteristics.

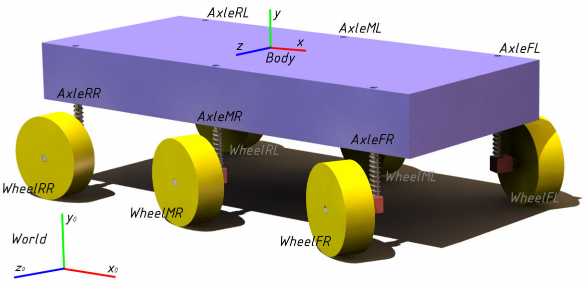


Fig. 1 Vehicle multibody model

2.2 Powertrain model

The powertrain is modelled as the system of a generic wheeled vehicle (Fig. 2) that in general consists of the following elements: engine, clutch, main gearbox, reduction gearbox, differential gear(s), and hub gears.

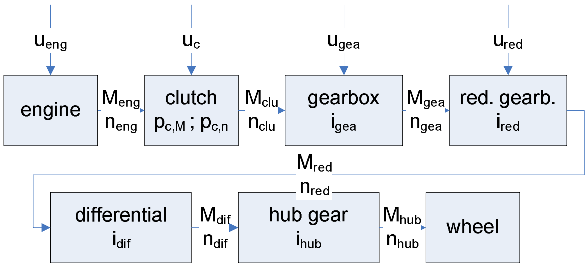


Fig. 2 A generic vehicle powertrain

Each power transmission element transfers torque and shaft angular velocity according to its transfer function.

Some transfer functions (e.g. those of fixed-ratio gears) are constant; others (e.g. those of gearboxes and clutches) are functions of additional user input u_i. Some power transmission elements may not be present in some vehicles (e.g. hub gears and reduction gearboxes are not common in ordinary passenger cars), in which case their transfer functions are constant and set to 1.

2.3 Braking system model

The braking system of the vehicle is modelled as a source of tangential force on the braked wheels, the amplitude of which depends on the position of the brake pedal as user input. Braking force can be individually applied to each of the wheels. The simulator provides a basic model of braking force reduction on the rear axle depending on the normal force on the rear axle. A simple model of slip-detection based anti-lock brake system (Fig. 3) is also implemented. The anti-lock braking system model can be switched on or off by an input parameter. When switched on, the model monitors the rotational velocity of the wheels and calculates longitudinal wheel slip s. Whenever its value rises above the specified threshold value s_{lim}, the braking force F_b is reduced from maximal braking force F_{max} to minimal braking force F_{min} to allow the wheels to start rotating again. This way the simulated vehicle retains its steering abilities even during hard braking.

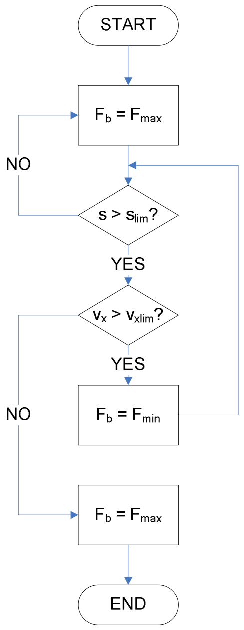


Fig. 3 Anti-lock braking system model flow chart

2.4 Steering system model

The steering system of the vehicle is modelled with a transfer function that transfers the steering wheel rotation angle as user input to rotation angle of the individual steered wheel. The model provides means of modelling of kinematic steering mechanism and its steering angle difference δ_{in} - δ_{out} to fulfil the Ackerman condition (Fig. 4).

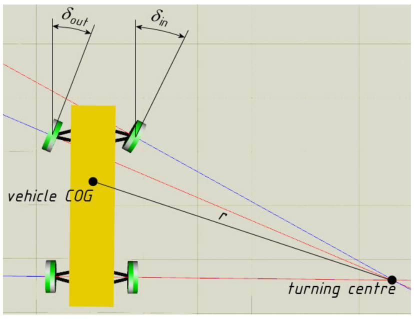


Fig. 4 The Ackerman condition

All the steering mechanism geometrical characteristics found on real vehicles (camber angle, castor angle, toe-in angles etc. [5, 6, 7]) are also accounted for and can be set by user parameters. Transfer functions for steering can be assigned for each axle of the vehicle separately. This way it is possible to model vehicles with unconventional steering systems (e.g. rear wheel steered fork lifts or vehicles with four wheel steering as shown in Fig. 5).

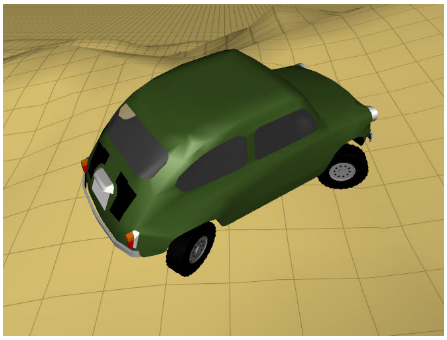


Fig. 5 An example four-wheel-steered vehicle

2.5 Vehicle – terrain interaction model

Terrain is modelled as a triangle mesh and used in collision algorithm to excite the vehicle dynamics model. The ODE collision detection system is used to determine the contacts between vehicle parts and the terrain geometry. The shape of the terrain triangle mesh is arbitrary and without restrictions for triangle dimensions. This way the memory required for storing triangle data and the number of vertices used in collision detection can be effectively reduced in the "flatter" areas of the terrain, whilst the more agitated areas can be represented by a larger number of triangles providing more accurate simulation. The point data to generate the terrain mesh can be obtained from various sources. These include field measurements and GIS data for existing real terrains, or different 3D modelling techniques for artificial terrains.

Apart from the driving surface model the terrain can include an arbitrary number of additional objects that can either be freely moving (i.e. interacting with other objects only through collisions) or connected to terrain and other objects by means of joints.

The forces that occur on the tyre-driving surface contact depend on many factors, of which the most significant are the longitudinal wheel slip s and lateral wheel slip angle α. These two quantities are computed for each wheel in every simulation step. The forces are modelled separately for the longitudinal and the lateral direction of the wheel using the simplified formulae as proposed by [8]. The code also includes statements for computing the aligning torque M_z on the steered wheels using a simplified formula as per [8]. Those statements can be included into the simulation step if steering wheel centering or torque feedback is required.

3 Software application for interactive vehicle simulation

The simulation models as described previously are incorporated into a software application named i3Drive that also includes components for display in virtual 3D environment, modules for polling control devices, a graphical user interface to control the application behaviour and components for simulation results export. Its advantage is that the user has access to all the relevant simulation parameters (regarding the vehicle, the terrain and the simulation intrinsics), which makes it possible to realistically simulate real vehicles on real terrains. Together with the possibility of real-time interactive driver input processing this makes the application useful for vehicle operator training. The structure of the application is schematically shown in Fig. 6.

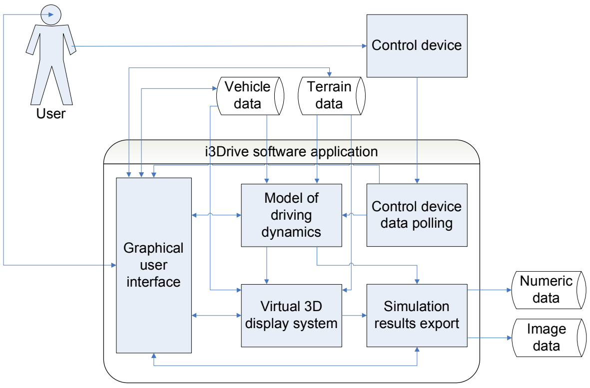
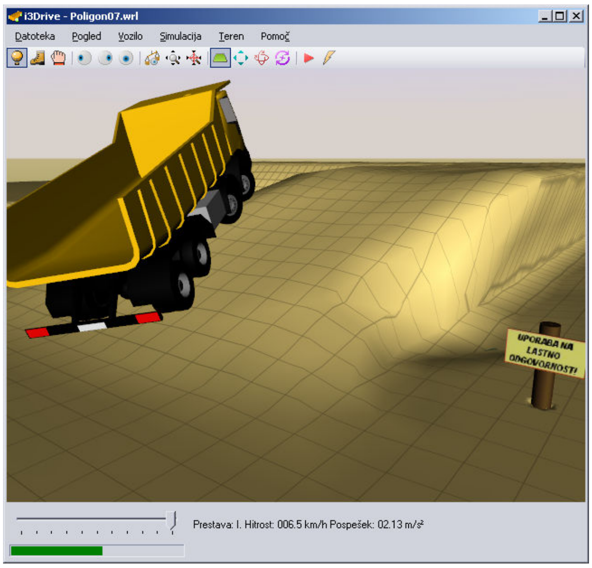


Fig. 6 i3Drive application scheme

3.1 The graphical user interface

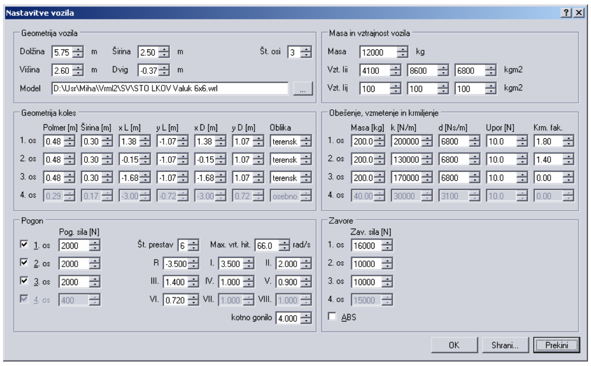
The largest part of the application main window (Fig. 7) is occupied by the display area where the visualisation in virtual 3D environment takes place. The user can control the simulation and display parameters with menu commands and toolbars and monitor the simulation status in the status area. Special care has been taken to provide easy access to common tasks such as switching viewpoints and changing navigation or motion mode or zooming to specific areas of view. This is why the commands to accomplish these tasks are also accessible with toolbar buttons and keyboard shortcut keys.

The user has access to all the relevant simulation settings and simulated vehicle parameters by means of input forms that open in separate windows (Fig. 8 and Fig. 9). This way it is possible to enter or change the vehicle parameters, control the simulation parameters (timings, behaviour, control device, sound), adjust the terrain settings (orientation, lighting conditions, colours) and insert objects into the simulation environment.



Prestava: I. Hitrost: 006.5 km/h Pospešek: 02.13 m/s²

Fig. 7 i3Drive main window



Geometrija vozila

Dolžina 5.75 m Širina 2.50 m Št. osi 3

Višina 2.60 m Dvig -0.37 m

Model D:\Usr\Miha\Vrml2\SV\STO LKOV Valuk 6x6.wrl

Masa in vztrajnost vozila

Masa 12000 kg

Vzt. Iii 4100 8600 6800 kgm2

Vzt. Iij 100 100 100 kgm2

Geometrija koles

	Polmer [m]	Širina [m]	x L [m]	y L [m]	x D [m]	y D [m]	Oblika
1. os	0.48	0.30	1.38	-1.07	1.38	1.07	terensk
2. os	0.48	0.30	-0.15	-1.07	-0.15	1.07	terensk
3. os	0.48	0.30	-1.68	-1.07	-1.68	1.07	terensk
4. os	0.29	0.17	-3.00	-0.72	-3.00	0.72	osebno

Obešenje, vzmetenje in krmiljenje

	Masa [kg]	k [N/m]	d [Ns/m]	Upor [N]	Krm. fak.
1. os	200.0	200000	6800	10.0	1.80
2. os	200.0	130000	6800	10.0	1.40
3. os	200.0	170000	6800	10.0	0.00
4. os	40.00	30000	3100	10.0	0.00

Pogon

	Pog. sila [N]
☑ 1. os	2000
☑ 2. os	2000
☑ 3. os	2000
☑ 4. os	400

Št. prestav 6 Max. vrt. hit. 66.0 rad/s

R -3.500 I. 3.500 II. 2.000

III. 1.400 IV. 1.000 V. 0.900

VI. 0.720 VII. 1.000 VIII. 1.000

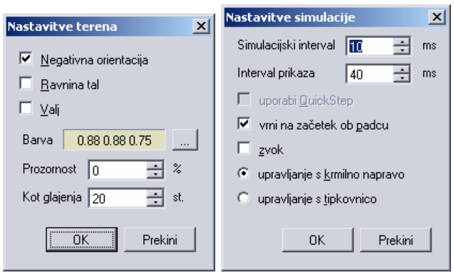
kotno gonilo 4.000

Zavore

	Zav. sila [N]
1. os	16000
2. os	10000
3. os	10000
4. os	15000

☐ ABS

Fig. 8 Vehicle settings window



☑ Negativna orientacija

☐ Ravnina tal

☐ Valj

Barva 0.88 0.88 0.75

Prozornost 0 %

Kot glajenja 20 st.

Simulacijski interval 10 ms

Interval prikaza 40 ms

☐ uporabi QuickStep

☑ vrni na začetek ob padcu

☐ zvok

● upravljanje s krmilno napravo

○ upravljanje s tipkovnico

Fig. 9 Terrain and simulation settings windows

3.2 The virtual 3D display subsystem

Simulated vehicle dynamics is presented in interactive virtual 3D environment. The user is represented by the virtual person, or avatar, that can be controlled independently of the simulated vehicle. This enables the user to observe the virtual 3D environment, and thus the driving simulation, from different perspectives and different points of view (Fig. 10). The avatar can be attached to the simulated vehicle to provide the "driver's view" or custom views of parts on the vehicle. To achieve a better view of the simulated vehicle when driving on larger driving surfaces, any fixed or moving viewpoint can be set to automatically follow the simulated vehicle by rotating the virtual camera.

Programmatically the display system is largely independent from the simulation engine and the mathematical model. This is achieved by running the simulation engine and the virtual 3D environment display in separate operating system threads assuring only synchronisation between the two timers. This way it is possible to achieve shorter simulation intervals to improve simulation accuracy and stability while keeping the display update interval long enough to ensure display in real time. On a 2600 MHz Pentium 4 computer with ATI Radeon 9600 graphics card at 1024×768 screen resolution the current version of i3Drive is capable of achieving the shortest simulation interval of 9 ms at a display frame rate of 25 frames per second when simulating a four-wheel vehicle on a driving surface consisting of 9800 triangles.

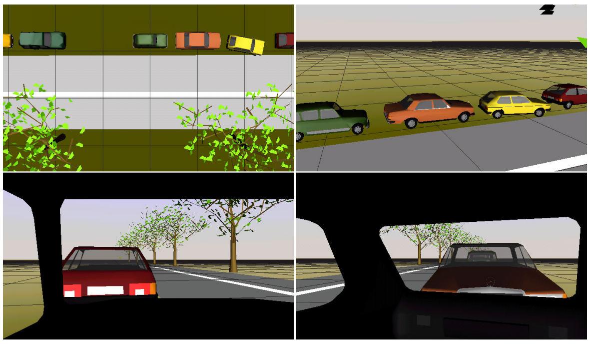


Fig. 10 Different views of the same scene

3.3 Simulated vehicle control

The inputs to the vehicle model (steering wheel angle, gas pedal position, brake pedal position, selected gear ratio, clutch state etc.) are delivered by means of a control device. This can either be a standard computer keyboard (for slow pace, low speed, less realistic simulations), a DirectInput compliant hardware control device or a combination of the two. The hardware control devices can range from standard commercial game controllers (joysticks and steering wheel/pedal combinations) to custom made controllers and detailed vehicle cockpit mock-ups.

Programmatically the control device polling is implemented in two separate subroutines, one for polling the hardware control device and another for polling the keyboard. During simulation, only one can be active at a time to minimise the required time for reading input data. The subroutine for polling the analogue control device can be set up to also monitor an arbitrary number of keys on the keyboard to provide access to additional vehicle controls that are not controlled by buttons on the control device.

In future, the actuators could be built into the control device and the simulation data can be used to provide motion- and force feedback to the user.

3.4 Data import and export

The software application can exchange input and output data with other applications. It can import vehicle data from ASCII files that can contain the full or partial set of parameters used in simulation. These data files can be generated by applications for vehicle database management [9] or obtained by measurements on real vehicle structures and elements.

The terrain data can be input from files in either VRML 2.0 or RDF (Adams Road File) format. From the data in the file the input functions automatically create a mesh for use in the simulation and its graphical representation for display.

The results of simulations can be exported as numerical data in spreadsheet form. They include kinematic values (displacements, velocities and accelerations) for bodies in the multibody system and vehicle control data (accelerator and brake pedal positions, steering wheel angle, selected gear etc.). Logging to the export file can be switched on or off during simulation by a menu entry or a keyboard shortcut key.

The results of simulations can also be exported as still images or digital video. Digital videos can be used for presenting the results independently from the main application. The application can encode video using encoders found on the host system. The advantage of simultaneous encoding is an accurate video produced as a result. Since frames are encoded at exactly the specified time intervals that correspond to simulation intervals multiples, the simulation stored in the video retains the original timescale and can thus be used for time-critical analyses.

4 Road geometry acquisition for simulation

To simulate vehicle driving dynamics on actual road sections (be it existing or in planning) it is essential that its sufficiently accurate 3D geometrical model is included into simulation. To enable import of road section surface data into various simulation software packages, it is convenient if the measurement data can be converted into an appropriate interface file formats automatically. For this purpose a software application [11] has been developed that converts the processed measurement data (measured road axis, calculated inclination and measured width) into the following file formats: AutoCAD DXF, VRML 1.0, VRML 2.0 - exports either surface or axis only or ADAMS Road File.

Models in these formats are directly applicable for visualisation (VRML) and for simulation in software packages such as PC-Crash (imports AutoCAD DXF format), ADAMS (imports RDF proprietary format) or i3Drive (imports either VRML 2.0 or RDF format).

5 3D geometrical model library

Vehicles and auxiliary objects used in virtual 3D environment are presented by their 3D geometrical models. The geometrical models can be of different precision depending on their use. The more precise models with higher polygon count are used in more detailed contact analysis, whilst lower polygon count models usually suffice for display and driving simulations with no or little contact between vehicle body and surrounding objects.

The models are derived from photographs of real vehicles using commercial photogrammetric software and 3D editing and modelling procedures. Their final format is VRML 2.0, which is suitable for use with all virtual 3D applications developed at the Department of Modelling in Engineering Sciences and Medicine [9], [10] and can easily be converted into other formats used by other simulation tools. The models are organised into a library that currently contains models of more than 150 commonly used road vehicles (Fig. 11) and numerous other models of humans, road signalisation and auxiliary objects.

Fig. 11 3D geometrical models of vehicles

6 Verification of simulation results

To evaluate the quality of simulation results computed by the i3Drive, the kinematic values (vehicle body centre of gravity velocities and accelerations) were compared to the curves obtained by measurement on a real vehicle and to the curves computed by PC-Crash as a representative of well-established commercial tools for simulating vehicle dynamics.

For this purpose a section of a road with several characteristic features as shown in Fig. 12 was selected. It includes a straight section and four curves of different curvatures, of which two were right and two left. The road was measured and modelled as described in section 4 of this paper. The 3D geometrical model of the road was used as the driving surface in PC-Crash v7.0a and i3Drive v0.5.0.202. The kinematic values were also measured on a real vehicle driving on the real road section. Tab. 1 shows the summary of simulation parameters.

Fig. 12 Test road section

Tab. 1 Summary of simulation parameters

Road section location	Hruševska, Bizoviška, Dobrunjska cesta, Ljubljana, Slovenia
Start point position (LAT, LON, ALT)	46,0399°N; 14,5625°E; 290 m
End point position (LAT, LON, ALT)	46,0383°N; 14,5753°E; 286 m
Road section length	1241 m (measured)
Vehicle	Opel Zafira A 2.0 DTI
Initial velocity	0 km/h
Target velocity	30 km/h
Simulation time	163 s

The simulated vehicle in i3Drive was interactively driven by the same driver as the real vehicle thereby maintaining the longitudinal velocity as close as possible to the specified target velocity, allowing to slow down to safe speed at the curves. The PC-Crash "virtual driver" was set up to follow the right traffic lane of the road section with a longitudinal velocity as close as possible to the specified target velocity. Fig. 13 shows a comparison of the longitudinal velocity curves and Fig. 14 a comparison of the acceleration amplitude curves for the three cases.

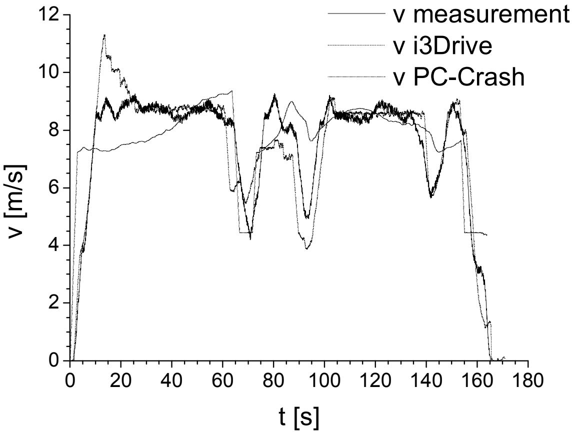


Fig. 13 Comparison of longitudinal velocity curves

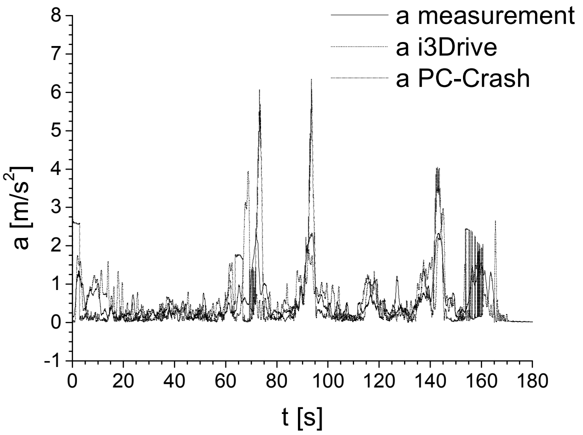


Fig. 14 Comparison of acceleration amplitude curves

7 Conclusion

The work presented in the paper shows how the principles of simulating road vehicle dynamics can be applied to build a software application that can interactively simulate driving dynamics of road vehicles with up to four axles on an arbitrary terrain. The i3Drive application in its current development state enables the user to drive a simulated vehicle in virtual 3D environment using a custom made control device that can resemble controls of a real vehicle. The simulated vehicle is described by a set of parameters that can easily be reviewed and adjusted through a comfortable graphical user interface and saved to vehicle data files for future use. The geometrical model of the driving surface, on which the simulation takes place, can be obtained either by measuring a real terrain or by modelling an artificial one. The terrain data can be read into the application from files in different formats, which facilitates direct comparisons of the results obtained by different simulation tools. A special supporting application has been developed to facilitate the conversion of measurement data obtained by a measuring vehicle to formats suitable for simulation. Apart from the driving surface itself the user can add other objects to the simulation environment and study interactions between them and the simulated vehicle. All the simulated kinematic values of all the bodies, composing the vehicle multibody system can be logged to a file during the simulation. This is useful for analysing the simulation results and comparing them to the results obtained from measurements or by other simulation tools. To make visual presentations based on the simulation results, i3Drive can export digital video simultaneously to simulation. Such digital video files are playable outside the i3Drive application but because of their precisely timed frames retain the time scale of the original simulation and can be used for time analyses.

The interactivity and the all-round flexibility make i3Drive a unique application among the commonly accessible tools for driving dynamics simulations. It finds its use in traffic accident analysis and vehicle evaluation whenever there is a need for interactive positioning of vehicles, visibility analysis or terrain exploration.

The next major step in the development of the i3Drive application will be implementation of a connection of the output data flow to actuators of a haptic interface, consisting of a powered steering wheel and movable driver's seat. This way the user will be provided with a motion- and force-feedback from the simulated vehicle and thus experience an even more realistic simulation.

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