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RESEARCH ARTICLE

# Real-time Look-ahead Cruise Control Simulator

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***Abstract***

*The paper introduces a hardware-in-the-loop (HIL) vehicle simulator built for testing and tuning a look-ahead cruise control algorithm considering forward road conditions. The aim of the vehicle simulator, apart from conducting real-time demonstrations and tests, is to create a HIL architecture which can be directly applied to a real heavy-duty vehicle formerly represented in TruckSim. By this means, several otherwise expensive road tests can be implemented with the simulator to increase the efficiency and reliability of the developed look-ahead control method.*

***Keywords***

*look-ahead, simulator, cruise control, optimal control*

## 1 Introduction and motivation

Vehicle simulators are widely used by automakers, industrial development companies and engineering research agencies as well. The purpose of a vehicle simulator is to develop and validate different driver models, vehicle dynamic control systems, etc. Since testing embedded control systems on real vehicles may depend on the availability of prototype vehicles, automotive companies tend to use more and more vehicle simulators in order to execute typical test scenarios, see Tsampardoukas, and Mouzakitis (2012). A hardware-in-the-loop (HIL) simulator based on a real vehicle was introduced in (Szalay et al., 2012), where a high-accuracy validated simulation software was attached to several hardware components. This simulator has already been used to set up longitudinal and lateral driver models based on driver experiments, see (Mihály and Gáspár, 2014). Also driver behavior, in terms of longitudinal dynamics, has been investigated and compared to the proposed look-ahead method, see Mihály et al. (2012; 2013).

Look-ahead control methods taking road conditions ahead of the vehicle into consideration have been studied by several authors, see Ivarsson et al. (2009), Nouveliere et al. (2008), Hellström et al. (2010), Passenberg et al. (2009), Kolmanovszky and Filev (2009), Hellström et al. (2009), Sahlholm and Johansson (2010). The look-ahead method implemented in the proposed vehicle simulator was introduced first in (Németh and Gáspár, 2011). Several studies have been conducted on this look-ahead algorithm, for example considering the effects of the tuning parameters were analyzed in (Németh and Gáspár, 2014).

The present paper introduces the development of a HIL vehicle simulator on which the look-ahead algorithm is tested and tuned. The presented vehicle simulator has several purposes. Firstly, it demonstrates the operation of the look-ahead cruise control and the effect of optimization parameter selection. Also, the look-ahead speed control can be compared to a conventional cruise control in a real-time environment. Moreover, the software and hardware components, which can be connected to a real vehicle, can be tested in TruckSim simulation environment.

The paper is organized as follows. Section 2 briefly decribes the look-ahead cruise control algorithm implemented in the

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simulator. Sections 3 introduces the logical and physical architecture of the complete HIL simulator with all of the hardware components involved. Section 4 deals with the high-fidelity TruckSim/Simulink real-time vehicle simulation environment, the linearized vehicle model, the speed controller design and shows the possible different driving modes. Finally, some concluding remarks are presented in Section 5.

## 2 Look-ahead control algorithm

The optimal velocity calculation for given road characteristics has already been introduced in (Németh and Gáspár, 2013), thus here only a short description is given. The look-ahead distance is divided into $n$ number of sections as depicted in Fig. 1.

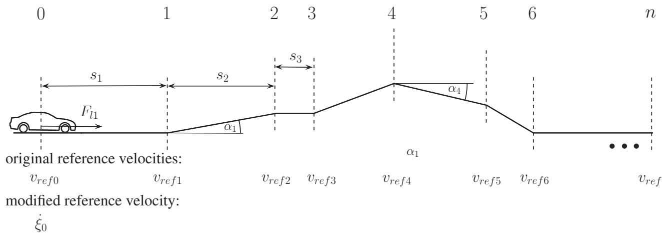


**Fig. 1** Division of predicted road

Assuming that road slope angle and the speed limit are known at each endpoints, the optimal velocity can be calculated as:

$$\lambda = \sqrt{\vartheta - 2s_1\left(1-Q\right)\left(\ddot{\xi}_0 + g\sin\alpha\right)}. \tag{1}$$

where

$$\vartheta = Qv_{ref,0}^2 + \sum_{i=1}^{n}\gamma_i v_{ref,i}^2 + \frac{2}{m}\sum_{i=1}^{n}\left(s_i F_{di,r}\sum_{j=i}^{n}\gamma_j\right). \tag{2}$$

where $s_i$ $i \in [1, n]$ is the length of the road section ($L = \sum s_i$), $v_{ref,i}$ is the speed limit at each section point, $F_{di,r} = mg\sin\alpha_i$ is the disturbance force from road inclinations, $Q$ and $\gamma_i$ are weights for the current and look-ahead reference velocities given as: $\gamma_1 + \gamma_2 + ... + \gamma_n + Q = 1$.

Two optimization problems must be solved: the longitudinal control force and the deviation from the reference velocity must be minimized. The two optimization criteria provide different solutions, hence a balance should be achieved. First, minimization of control force $F_{l1}^2 \to \min$ can be achieved by solving the following quadratic optimization problem:

$$\bar{F}_{l1}^2 = \left(\beta_0\left(\bar{Q}\right) + \beta_1\left(\bar{Q}\right)\bar{\gamma}_1 + \ldots + \beta_n\left(\bar{Q}\right)\bar{\gamma}_n\right)^2 \to \min \tag{3}$$

with the following constrains $0 \le \bar{Q},\ \bar{\gamma}_i \le 1$ and $\bar{Q} + \sum\gamma_i = 1$.

Second, the minimization of the speed differences from the speed limits must be formulated as:

$$\left|v_{ref,0} - \dot{\xi}_0\right| \to \min \tag{4}$$

The optimal solution for the latter is selecting $\breve{Q} = 1$ and $\breve{\gamma}_i = 0, i \in \left[1, n\right]$.

The appropriate balance is set by two performance weights $R_1$ and $R_2$. Performance weight $R_1$ $(0 \le R_1 \le 1)$ shows the importance of energy minimization, while performance weight $R_2$ $(0 \le R_2 \le 1)$ is connected to the minimization of travel time, where $R_1 + R_2 = 1$. Hence, a balance between the optimizations tasks can be achieved by using the performance weights $R_1$ and $R_2$ as follows:

$$Q = R_1\bar{Q} + R_2\breve{Q} = 1 - R_1\left(1 - \bar{Q}\right) \tag{5a}$$

$$\gamma_i = R_1\bar{\gamma}_i + R_2\breve{\gamma}_i = R_1\bar{\gamma}_i, \quad i \in \left\{1,..,n\right\} \tag{5b}$$

Note, that in order to increase computational efficiency an analytical solution is given for the look-ahead optimization algorithm. The flowchart of the look-ahead algorithm is depicted in Fig. 2. Here, the vehicle physical details are considered as constant parameters, while the tuning parameters (look-ahead distance: $L$, performance weight: $R_1$, number of division points: $n$) are set by the driver as detailed in Section 3. These tuning parameters are the inputs for the optimization algorithm, which uses the vehicle actual position in the calculation of the disturbance forces. Note, that the algorithm cycle time depends on the $n$ parameter set by the driver. The constraining is necessary, because MicroAutobox II has limited computing capacity.

The look-ahead control algorithm shown in Fig. 2 is evaluated as follows. First, the tuning parameters given by the driver and received from TruckSim are set. Next, the resistance forces $F_{di}$ $i \in [1, n]$ depending on the angle of the road for each of the look-ahead segments are calculated, where $n$ represents the number of division points and $L$ stands for the total look-ahead distance. The next cycle calculates all of the longitudinal drive/brake forces $F_{li}$ $i \in [1, n]$ for each road segment, by which the reference velocities $v_{ref,i}$ $i \in [1, n]$ (speed limits) can be reached . If all of the longitudinal forces have the same sign, the absolute minimal value is chosen, else the longitudinal force is set to be zero. The optimal acceleration is then given by dividing the optimal control force with the vehicle mass, while the optimal velocity is finally calculated by integrating the optimal acceleration.

## 3 Architecture of the vehicle simulator

The logical structure of the simulator is shown in Fig. 3. The top SIMULATOR block includes the driver environment, which has the following hardware elements: a gaming steering wheel with force feedback, a pedal set and a gearbox appliedto a gaming driver seat, a projector used for visualization and a computer on which the real-time version of TruckSim software is running. The driver sits on the simulator seat operating the steering wheel and pedals, thus controlling the simulated vehicle in TruckSim. Hence, TruckSim generates the vehicle dynamics and the visualization of the environment, which is projected in front of the driver. Driver interventions (steering, braking, accelerating, etc.) are thus based on the visual and audio feedback. By pushing the appropriate buttons on the steering wheel, the driver can also activate the conventional and the look-ahead cruise control. The latter can be tuned by changing the parameters of the look-ahead algorithm presented in Németh and Gáspár (2011). Note that the simulated GPS signals are sent to the MAP block, while the measured vehicle signals are sent to the OPTIMIZATION block.

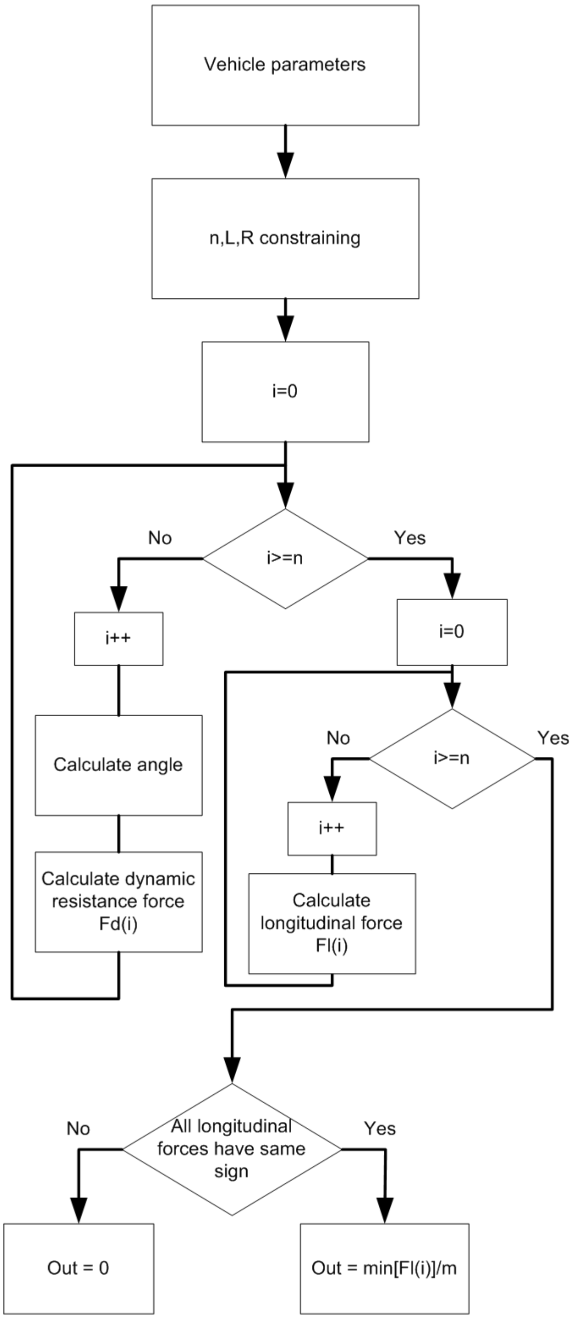

Vehicle parameters
n,L,R constraining
i=0
No
i>=n
Yes
i++
i=0
Calculate angle
No
i>=n
Yes
i++
Calculate dynamic resistance force Fd(i)
Calculate longitudinal force Fl(i)
No
All longitudinal forces have same sign
Yes
Out = 0
Out = min[Fl(i)]/m

**Fig. 2** Flowchart of the control algorithm

The purpose of the MAP block is to define the look-ahead road information based on the current GPS position of the vehicle. For the given look-ahead distance, the road elevations, speed limits, weather and traffic conditions are provided. This road information is given by an industrial computer, on which a real-time MATLAB application generates the necessary data from different databases (Google Maps, Open Weather Map, etc.). The road information on the look-ahead distance is then sent to the OPTIMIZATIONblock.

Based on the measured vehicle signals from the SIMULATOR block and the road information provided by the MAP block, the OPTIMIZATION block calculates the optimal velocity for the vehicle. The optimization algorithm runs on dSPACE MicroAutoBox II and communicates via CAN signals with the SIMULATOR block. Hence, when the look-ahead cruise control is activated by the driver, the optimal velocity is chosen as the reference velocity for the PID speed controller in the SIMULATOR block. Note that at the same timethe current and optimal velocities along with the optimization parameters are sent back to the MAP block.

The MAP AND OPTIMIZATION VISUALIZATION block is for the visualization of the road topography and the optimization parameters used by the look-ahead controller. The map is generated by the industrial computer in the MAP block alongside with the current andreference speeds and the optimization parameters are shown on a tablet for the driver.

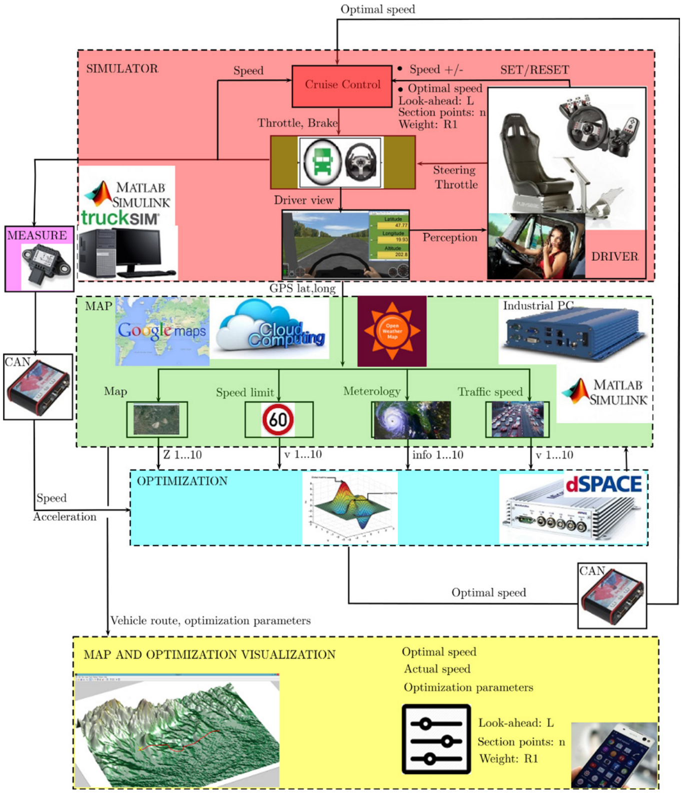


**Fig. 3** Simulator flow chart

The technical architecture of the simulator is shown in Fig. 4. The real-time TruckSim simulation running on the desktop computer generates the virtual GPS signals (longitude, latitude, altitude), which are sent to the industrial computer via RS-232 serial port. Note that in the real vehicle these signals are provided by the on-board GPS device. The desktop computer sends the velocity and acceleration data to Microsoft dSPACE Autobox II via CAN messages, which are handled by a CANcaseXL card built in the desktop computer. The industrial computer is connected via Ethernet and WiFi Router to the internet databases (Google Maps)and sends the predicted road information to the Microsoft dSPACE Autobox II via RS-232 serial port. The current and optimal velocities, the road map and the optimization parameters are sent to a tablet application via WiFi communciation. Note that in the technical architecture shown in Fig. 4 it is clearly visible how the hardware components can be isolated from the vehicle simulator and installed on a real vehicle.

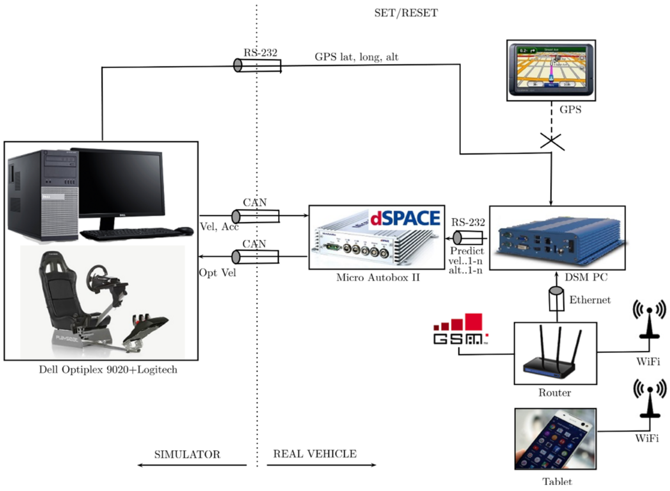


**Fig. 4** Simulator technical architetcure

## 4 Real-time TruckSim simulator

### 4.1 Simulation environment

The real-time version of TruckSim software is used for the vehicle simulations and it contains high complexity models of trucks, lorries, buses and other heavy-duty vehicles. TruckSim contains several validated models of powertrains, braking systems, steering systems, wheels, etc. TruckSim also creates a package consisting of multiple files based on a set of vehicle parameters, traffic environment, weather parameters, which are passed to MATLAB. The Simulink model file contains an S-function block, which receives the file package from TruckSim and runs the S-functions related to the simulated vehicle. Thus, the simulation can be run with the file package generated by TruckSim, while a real-time animation of the vehicle motion is produced.

The simulation environment is shown in Fig. 5. The road inclinations and curves are defined in TruckSim based on real data provided by different databases. The driver sitting in the driver seat operates the gaming steering wheel and defines the inputs based on the visual perception. Note that when thecruise control (conventional or look-ahead) is switched on, only steering input is needed from the driver. TruckSim/Simulink generates the vehicle dynamics and the visualization of the simulation. Here, a conventional two-axle tour bus is simulated with a 150 kW engine, 5 speed automatic transmission.

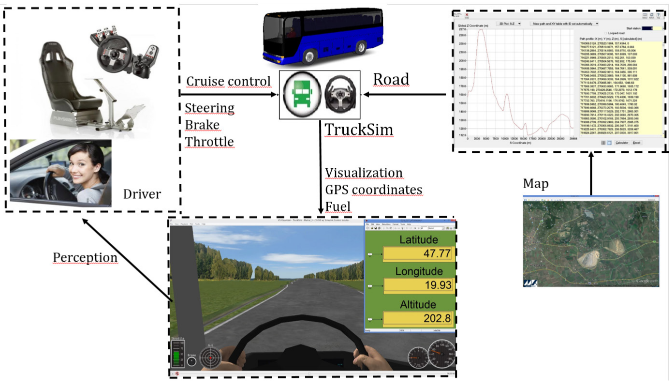


**Fig. 5** Real-time simulation with TruckSim

### 4.2 Vehicle model

For the longitudinal control of the simulated vehicle a simplified vehicle model is introduced. Since the output of PI speed controller is a positive or negative longitudinal force, the low-level controllers must address the corresponding physical actuators (see Fig. 6). Thus, for setting the desired acceleration the throttle angle of the engine must be adjusted, while for braking the brake pressure must be set. Hence, by linearizing the vehicle model around the operation points, the actuator inputs can be defined accurately to meet the desired acceleration given by the reference longitudinal force of the speed controller.

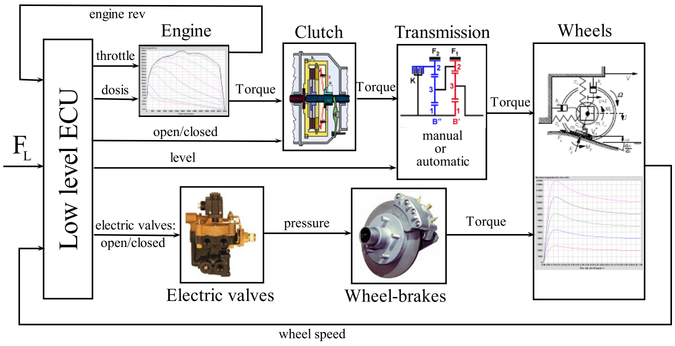


**Fig. 6** Vehicle model

### 4.3 Design of PI speed controller

The PI speed controller has been tuned by simulations for a specific vehicle in the following steps:

Requirement definition: minimum overshoot and steady-state error, minimal value of regulatory power.

During the PI control design a feedback linearization method has been applied, as already introduced in (Mayr, 1994). Thus, the highly non-linear components of the vehicle dynamics (aerodynamic drag, road slope resistance, rolling resistance) are calculated by using measurement data. These non-linear resistance forces are added to those provided by the speed controller. The method has the advantage that by separating the calculated nonlinearities a simple linear PID controller can be realized for the highly non-linear system.

The feedback linearized PI speed controller and the vehicle model have been created in MATLAB/Simulink and connected to TruckSim environment (see Fig. 7). A predefined hilly route has been provided with a jump in the reference speed signal. Also, a performance function has been defined as a weighted (Q,R) amount of the square integral, the longitudinal force and the velocity tracking error.

The simulation is run by calling a MATLAB function. For a given performance weighting Q and R related to the importance of velocity tracking error minimization or longitudinal control force minimization, an optimization routine is called and the TruckSim simulation is run with the given value of P and I parameters. The TruckSim simulation is run cyclically while P and I parameters are altered until the previously defined performance function is minimized. Hence, by the appropriate selection of Q and R weightings, the PI controller can be tuned to guarantee both minimal overshooting and steady state error while the control force is kept small.

Note that in the performance weighing selection (Q,R) in the controller tuning process listed above, engineering and practical considerations are used.

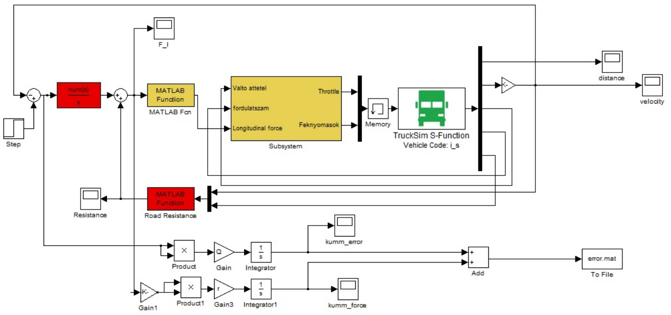


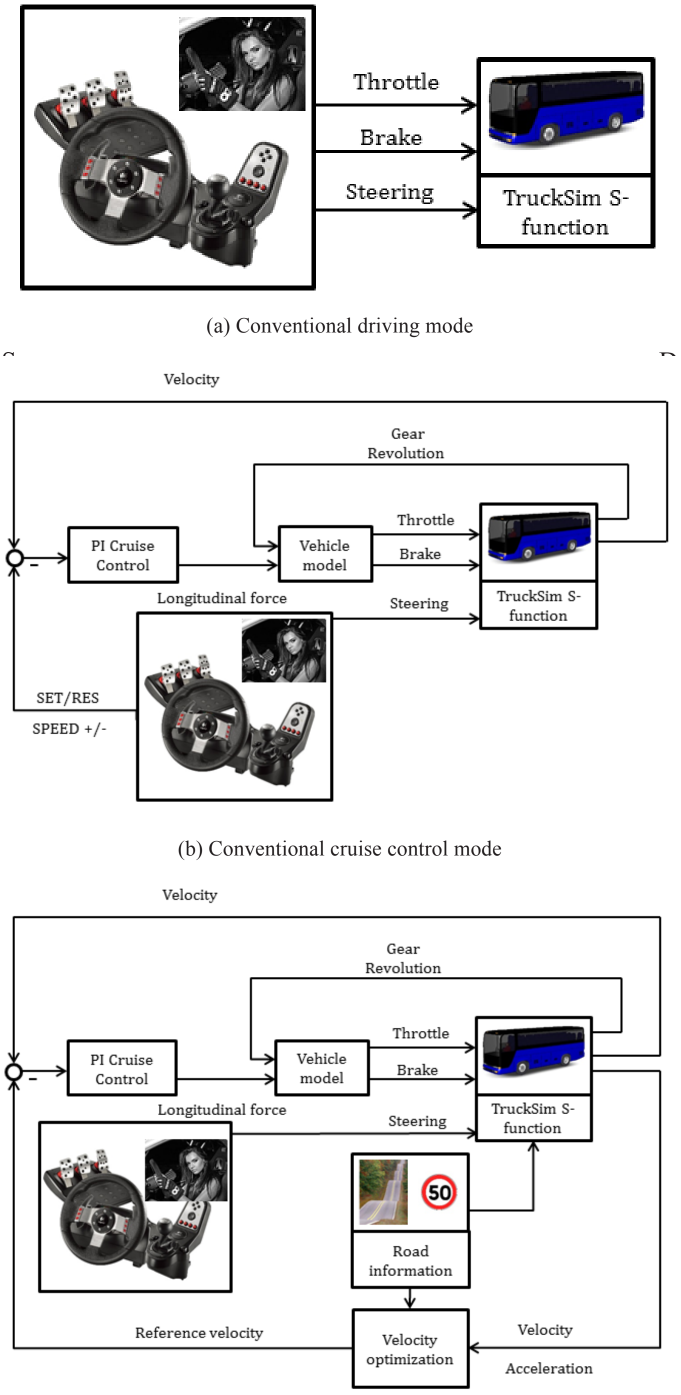
**Fig. 7** Speed controller design

### 4.4 Simulation modes

The vehicle simulator can be driven in three different driving modes, which can be selected by pushing different buttons on the steering wheel.

When the real-time simulation starts, the vehicle can be driven manually with the manipulation of the steering wheel and the brake/accelerator pedals (see Fig. 8(a)). In this mode, the speed of the vehicle only depends on the driver's intention and vehicle capability.

By pushing the SET/RESET button the conventional cruise control detailed in Section 3 is activated and the current speed of the vehicle is set as the reference velocity (see Fig. 8(b)). Note that this reference velocity can be incremented/decremented with 1km/h steps by pulling the paddles behind the steering wheel. In this driving mode, only steering intervention is required by the driver while the vehicle generally follows the speed limit.



(a) Conventional driving mode

(b) Conventional cruise control mode

(c) Look-ahead cruise control mode

**Fig. 8** Simulator driving modes

Finally, by pushing the OPTIMAL button on the steering wheel the look-ahead cruise control is activated (see Fig. 8(c)). In this mode, based on the given road information (speed limits, road inclinations) the bus follows an optimal velocity profile with the consideration of both energy and traveling time minimization. Note that on the gearbox console further buttons are selected for tuning the look-ahead algorithm in real-time driving mode. Hence, with gearbox console buttons the look-ahead distance $L \in [0,5000]$ can be modified by 550 m steps, the number of look-ahead section points $n \in [0,100]$ can be incremented/decremented with 10 steps, while the optimization parameter $R_1 \in [0,1]$ can also be modified by 0.1 steps. Note, that $R_1 + R_2 = 1$ implies that defining optimization parameter $R_1$ also determines $R_2$, since $R_2 = 1 - R_1$. In this driving mode only steering intervention is needed by the driver while the effect of look-ahead parameter tuning can be tested in realtime.

## 5 Conclusion

In the paper a real-time HIL driving simulator has been presented with the aim of testing and tuning a look-ahead cruise controller. The simulator has been built in such a way that the hardware components can easily be isolated from the real-time TruckSim simulation environment and installed on a real vehicle for road testing. The vehicle modeling and speed control design have been described, as well as the different driving modes provided by the simulator. The main contribution of the HIL simulator is that the look-ahead controller can be tested and tuned in a real-time environment.

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## References

Hellström, E., Åslund, J., Nielsen, L. (2010). Horizon length and fuel equivalents for fuel-optimal look-ahead control. In: *6th IFAC Symposium Advances in Automatic Control. IFAC Proceedings Volumes*. 43(7), pp. 360-368. https://doi.org/10.3182/20100712-3-DE-2013.00114

Hellström, E., Ivarsson, M., Åslund, J., Nielsen, L. (2009). Look-ahead control for heavy trucks to minimize trip time and fuel consumption. *Control Engineering Practice*. 17(2), pp. 245–254. https://doi.org/10.1016/j.conengprac.2008.07.005

Ivarsson, M., Åslund, J., Nielsen, L. (2009). Look ahead control - consequences of a non-linear fuel map on truck fuel consumption. *Proceedings of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering*. 223(10), pp. 1223–1238. https://doi.org/10.1243%2F09544070JAUTO1131

Kolmanovsky, I. V., Filev, D. P. (2009). Stochastic optimal control of systems with soft constraints and opportunities for automotive applications. In: *18th IEEEConference on Control Applications. Part of 2009 IEEE Multi-conference on Systems and Control.* Saint Petersburgh, Russia, Jul. 8-10, 2009, pp. 1265-1270. https://doi.org/10.1109/CCA.2009.5280822

Mayr, R. (1994). Intelligent cruisec on trol for vehicles based on feedback linearization. In: *Proceedings of the 1994 American Control Conference*, 1, pp. 16–20 https://doi.org/10.1109/ACC.1994.751684

Mihály, A., Gáspár, P. (2014). Identification of a linear driver modelbased on simulator experiments. *2014 IEEE 9th International Symposium on Applied Computational Intelligence and Informatics*. Timisoara,Romania, May 15-17. pp. 13-18. https://doi.org/10.1109/SACI.2014.6840057

Mihály, A., Németh, B., Gáspár, P. (2012). Analysis of driver behavior related to look-ahead control. *IFAC Proceedings Volumes*. 45(24), pp. 268-273. https://doi.org/10.3182/20120912-3-BG-2031.00056

Mihály, A., Németh, B., Gáspár, P. (2013). Enhancement of driver speed based on multi-criteria optimization. *Periodica Polytechnica Transportation Engineering*. 41(1), pp. 71-76. https://doi.org/10.3311/PPtr.7103

Németh, B., Gáspár, P. (2011). Road inclination sin the design of LPV-based adaptive cruise control. In: *Proceedings of 18th IFAC World Congress*. Milano, Italy, Aug. 28-Sep. 02, 2011, pp. 2202-2207. https://doi.org/10.3182/20110828-6-IT-1002.00932

Németh, B., Gáspár, P. (2013). Design of vehicle cruise control using road inclinations. *International Journal of Vehicle Autonomous Systems*. 11(4), pp. 313–333. https://doi.org/10.1504/IJVAS.2013.056651

Németh, B., Gáspár, P. (2014). Model-based sensitivity analysis of the look-ahead cruise control. In: *15th IEEE International Symposium on Computational Intelligence and Informatics*. Budapest, Hungary. Nov. 19-21. 2014. pp. 103-108. https://doi.org/10.1109/CINTI.2014.7028657

Nouveliere, L., Braci, M., Menhour, L., Luu, H. T., Mammar, S. (2008). Fuel consumption optimization for a city bus. In: UKACC Control Conference.

Passenberg, B., Kock, P., Stursberg, O. (2009). Combined time and fuel optimal driving of trucks based on a hybridmodel. In: *2009 European Control Conference* Budapest, Hungary. Aug. 23-26. 2009. pp. 4955-4960.

Sahlholm, P., Johansson, K. H. (2010). Road grade estimation for look-ahead measurement runs. *Control Engineering Practice.* 19(11), pp. 1328-1341. https://doi.org/10.1016/j.conengprac.2009.09.007

Szalay, Z., Gáspár, P., Kánya, Z., Nagy. D. (2012). Development of vehicle simulator based on a real car for research and education purposes. In: *Proceedingsof the FISITA 2012 World Automotive Congress.* 196, pp. 1301–1312. https://doi.org/ 10.1007/978-3-642-33738-3_31

Tsampardoukas, G., Mouzakitis, A. (2012). Deployment of full vehicles imulator for electrical control system validation. In: *Proceedings of 2012 UKACC International Conference on Control*. pp. 551–556. https://doi.org/10.1109/CONTROL.2012.6334689