A co-simulation environment for high-fidelity virtual prototyping of vehicle systems

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Abstract: Computer simulation is being increasingly used for virtual prototyping of ground vehicles ahead of building actual hardware prototypes. This paper describes a methodology to co-simulate, with high fidelity and in one computational framework, all of the main vehicle subsystems for improved engineering design. The approach leverages the capabilities of three software packages (ADAMS, PSAT, FTire) to simulate vehicle kinematics/dynamics, powertrain dynamics, and tyre-terrain contact in one unified environment. As a result, information about forces in vehicle components, driver comfort, maximum cornering speed, fuel efficiency and engine emission details can all be obtained at the same time. This data is relevant when used for comparing competing designs that draw on different values of vehicle parameters (inertia, material, suspension properties, stiffness), powertrain system settings for conventional, hybrid, or fuel cell topologies, and tyre-terrain interface parameters (road profile, tyre pressure, tread). A generic sedan and US army's high mobility multipurpose wheeled vehicle (HMMWV), both with conventional powertrain systems, are used to demonstrate the proposed simulation framework.

Keywords: co-simulation; vehicle dynamics; powertrain model; tyre model.

Reference to this paper should be made as follows: Datar, M., Stanciulescu, I. and Negrut, D. (2012) 'A co-simulation environment for high-fidelity virtual prototyping of vehicle systems', *Int. J. Vehicle Systems Modelling and Testing*, Vol. 7, No. 1, pp.54–72.

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1 Introduction

Over the last decade, virtual prototyping, drawing on computer aided design and computer aided engineering (CAD/CAE), has become an important component of the product life cycle in automotive industry. This trend is motivated by economic factors; i.e., reduced cost and time to market due to partial replacement of physical testing with computer simulation. It is clearly desirable to gain a reliable perspective on the behaviour of a system early in the design stage, long before building costly prototypes. The potential benefits of virtual prototyping further increases when the final system is an assembly of components/subsystems contributed by several manufacturers at different geographic locations. These subsystems might be in various stages of development, and building a complete physical prototype is either impractical (due to cost and time constraints) or outright impossible.

The increased role and impact of virtual prototyping has fuelled a constant increase in the complexity of simulation models employed to understand and control system dynamics (Briggs et al., 1990; Lin et al., 2001; Butler et al., 2002; Zorriassatine et al., 2003; Blundell and Harty, 2004; Choi and Chan, 2004). Today, the state of the art in vehicle virtual prototyping (Ellis, 2002) in the automobile industry has reached a level where the dynamics of a vehicle are analysed through simulation. Also, several simulation tools are available to model and analyse the performance of a powertrain system. However, a simulation environment that analyses the vehicle model together with an accurate powertrain model continues to elude the industry. This paper addresses these limitations and outlines a virtual environment for high-fidelity vehicle simulation by combining third party packages for vehicle-tyre-terrain and powertrain simulation.

Specifically, this effort is aimed at integrating 'all' of the key vehicle subsystems: vehicle body, tyre, powertrain, driver, and terrain into one single high-fidelity unified simulation environment. A similar approach, by Kim et al. (2005) involved the use of ADAMS/Car-MATLAB co-simulation to evaluate the performance of several vehicle stability control algorithms for a four wheel drive hybrid electric vehicle. Danesin et al. (2001) explored a methodology to investigate vehicle dynamics with real time dampers (active suspension). The vehicle chosen for this study was a customised Fiat car modelled using ADAMS, and the analysis drew on a MATLAB/Simulink – ADAMS co-simulation. Liao and Du (2001) studied the performance of an electric power steering (EPS) system. For their study, again ADAMS and MATLAB were utilised in a co-simulation environment to model and analyse a vehicle equipped with an EPS control system. ADAMS was utilised for computing the vehicle dynamics while MATLAB handled the EPS control system. Mancosu and Arosio (2005) also used co-simulation between ADAMS and MATLAB/Simulink. They relied on a sophisticated multi-body vehicle model developed in ADAMS, while MATLAB/Simulink provided the analysis environment for subsystems like electronic control systems, the braking system and the steering system.

The co-simulation framework presented in this paper integrates, for the first time, high fidelity vehicle dynamics with a high fidelity and comprehensive powertrain model. On one hand, this allows insight into how the dynamics of a vehicle affect fuel consumption, chemical composition of emission, and vehicle control strategies. On the other hand, the choice of powertrain system also influences the dynamics of the vehicle. For instance, variations in drive shaft torque affects vehicle handling (Shim and Zhang, 2006), and the maximum achievable acceleration of the vehicle is limited by maximum torque at the driving wheels along with the traction force at the tyre footprint (Jazar, 2008). The goal of developing this co-simulation framework is to capture the interaction between the powertrain and the rest of the vehicle in order to better predict, through simulation, the overall dynamics of the vehicle.

The vehicle and powertrain models used in this framework are detailed in Sections 2 and 3 with description of the co-simulation setup in Section 4. Numerical results with a generic sedan vehicle and army's high mobility multipurpose wheeled vehicle (HMMWV) are presented in Section 5 followed by conclusions in Section 6.

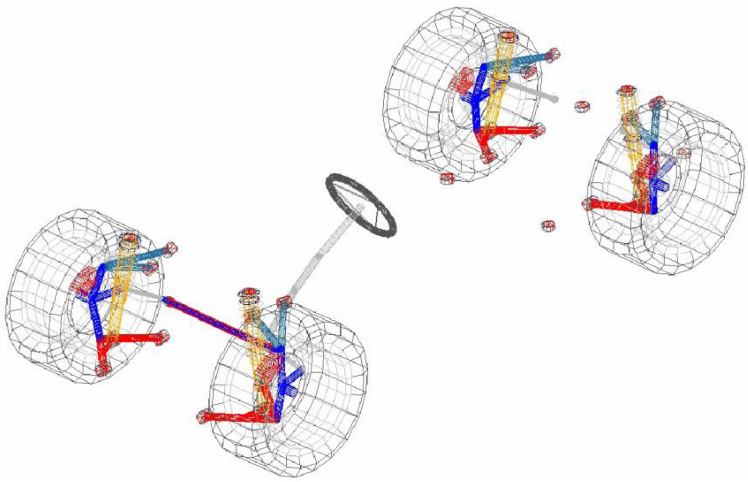
2 High fidelity vehicle and tyre models

The vehicle (without powertrain) is modelled using a commercially available-off-the-shelf (COTS) package ADAMS (MSC.Software, 2005). This package is widely adopted in the industry for ground vehicle simulations of both light and heavy-duty vehicles fitted with subsystems (steering, suspension, etc.) of chosen type (for instance Ackerman

Arm/McPherson Strut for suspension). Using this package, a fully functional model of a generic sedan vehicle and a high accuracy HMMWV model (Aardema, 1988) are generated for performing numerical simulations under the co-simulation framework.

Figure 1 shows the topology of a generic vehicle with front and rear suspension, wheels, and steering subsystems. The chassis of the vehicle, which is not shown, is modelled as a single component having appropriate mass-inertia properties. The entire vehicle model, with the exception of tyres, is defined in ADAMS. The tyres are modelled using a software package called flexible ring tyre (FTire). FTire (Gipser, 2005) can be used in multi-body system models for vehicle ride comfort investigations as well as for other vehicle dynamics simulations on even or uneven roadways. Used with the ADAMS vehicle model, it is internally invoked by ADAMS when performing a vehicle simulation. Amongst the other possible choices for the tyre model are Pacejka tyre model (Pacejka and Bakker, 1992) and University of Arizona tyre model (Gim, 1988). However, these models are valid on rather smooth roads where the wavelength of the road obstacles is not smaller than the tyre circumference. Hence, for a non-smooth road with smaller obstacle wavelengths FTire model is used as it is able to capture the non-linear tyre enveloping effects.

Figure 1 A generic vehicle model (chassis not shown) (see online version for colours)

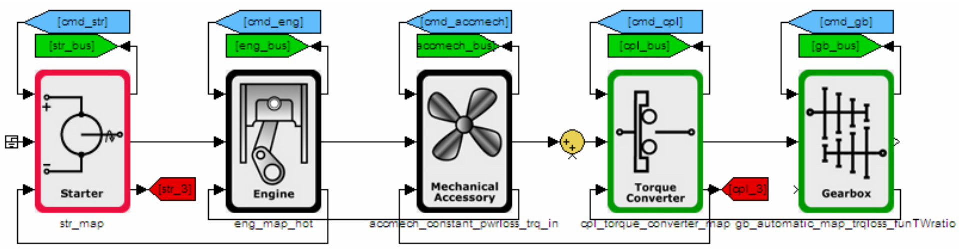


3 Powertrain model

A high-fidelity powertrain model/simulation capability is of utmost importance for this effort as one of the strategic goals of the simulation environment is the analysis of different powertrain topologies to determine their fuel efficiencies and resulting environmental footprint. The powertrain system model in ADAMS is simple and not extensively validated. Further, it can only represent conventional powertrain systems. As a result, more advanced powertrain system simulation capability is desired. With a proven-through-validation ability to model a broad spectrum of configurations and subcomponents, the COTS package powertrain systems analysis toolkit (PSAT, Rousseau and Pagerit, 2001) is selected herein for powertrain simulations.

Powertrain models in PSAT are built using MATLAB/Simulink by selecting sub-component models for the engine and/or motor, starter, battery, differential, and gear box as illustrated in Figure 2. PSAT can simulate several predefined configurations including electric, fuel cell, and hybrid (parallel, series, power split, series-parallel, etc.) alongside conventional powertrains. It can be used to evaluate fuel consumption and performance for a variety of driving cycles, to develop realistic control strategies, and to select drivetrain components (Rousseau et al., 2004).

Figure 2 PSAT Simulink model (see online version for colours)



4 Co-simulation enabled virtual prototyping

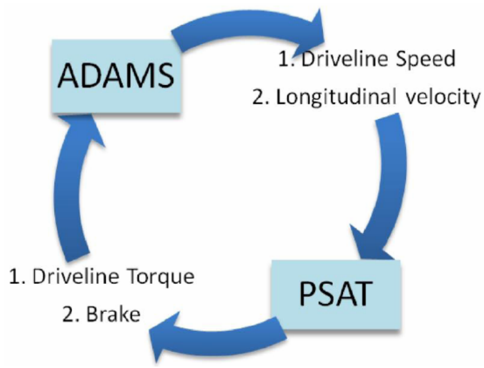
As described in the previous section, PSAT can be used to simulate several types of powertrain systems with high accuracy. At the same time, ADAMS offers high fidelity chassis, suspension, steering, and driver models. To leverage the strengths of both packages, the vehicle model in ADAMS is interfaced with the powertrain model represented in PSAT.

At the cornerstone of this approach lies a co-simulation backbone that relies on data conduits for transparently exchanging information between the participating simulation packages. PSAT provides the numerical value for wheel torque and braking demand to the ADAMS model. In return, the ADAMS vehicle model gives feedback to PSAT about the vehicle's longitudinal velocity and driveline speed (see Figure 3). Sensing the speed of the vehicle, the PSAT powertrain model will adjust the output torque and brake demand so that the ADAMS vehicle matches the desired velocity profile (specified in PSAT) as closely as possible. The values of the aforementioned variables are exchanged, at every simulation time step, back and forth between PSAT and ADAMS. Hence, in order to keep them in sync, the size of the simulation time step used to advance the time evolution of the dynamics of the system should be identical in both ADAMS and PSAT. The connection between ADAMS and PSAT is established in a MATLAB/Simulink environment by generating Simulink models of both the ADAMS vehicle and the PSAT powertrain.

A native plugin called ADAM/Controls is used to generate the Simulink model of an ADAMS vehicle. Since PSAT powertrain is already modelled using MATLAB/Simulink, it can be used as is.

Note that PSAT does have a chassis-tyre-terrain model. However, it is very simplified and hence cannot be used to control/capture accurately the dynamics of the vehicle (location of upper ball joint in the suspension cannot specified and the reaction force in this joint cannot extracted).

Figure 3 Flow of information between ADAMS and PSAT at each time step (see online version for colours)



Consequently, the PSAT native powertrain model is obtained by disconnecting it from the chassis-tyre-terrain model. A Simulink model of PSAT powertrain is shown in Figure 2 while Figure 4 shows the same for the ADAMS vehicle model. The desired drive cycle (velocity profile as a function of time or distance travelled) for performing the vehicle simulation is specified in PSAT. Once the connection between the simulink model of ADAMS vehicle and PSAT powertrain is established, the PSAT powertrain will sense and control the ADAMS vehicle model based on the desired drive cycle (Datar and Negrut, 2007). A Simulink model with appropriate connections between the PSAT and the ADAMS components is shown in Figure 5. A flowchart of the steps involved in setting up the co-simulation framework is laid out in Figure 6.

The capability described herein can be used to assemble a vehicle and run it in a virtual environment by specifying both vehicle and powertrain subsystem components at various levels of fidelity using a mix-and-match approach.

Figure 4 ADAMS block (see online version for colours)

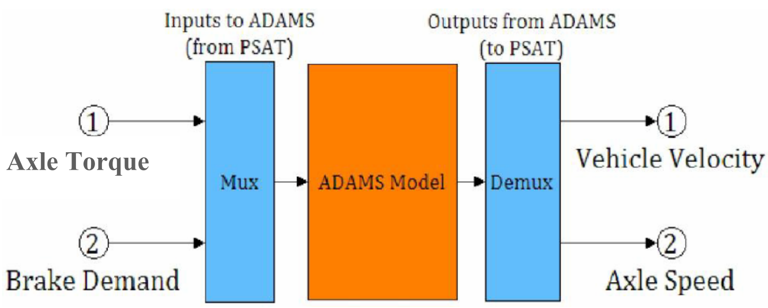


Figure 5 Integration of high-fidelity ADAMS vehicle model and PSAT powertrain (see online version for colours)

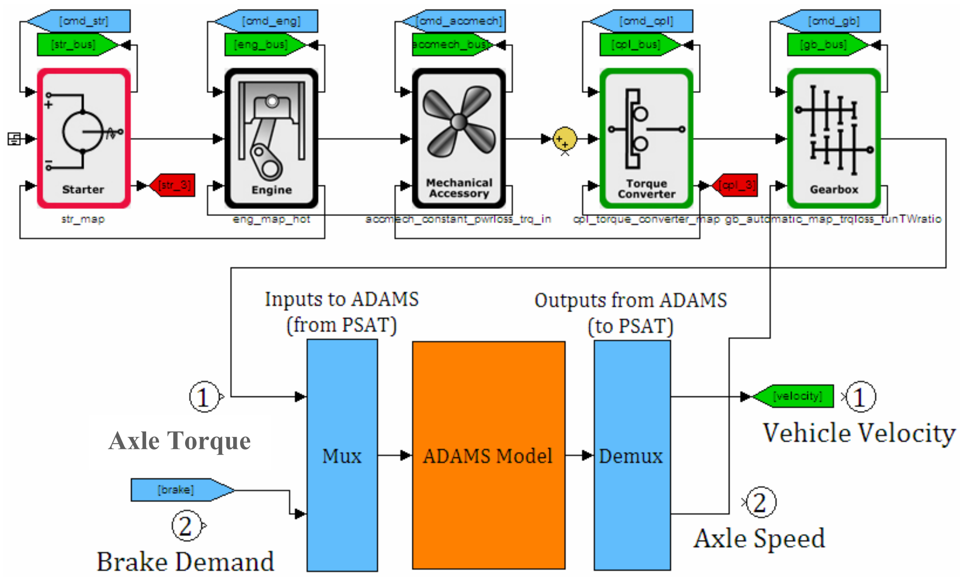
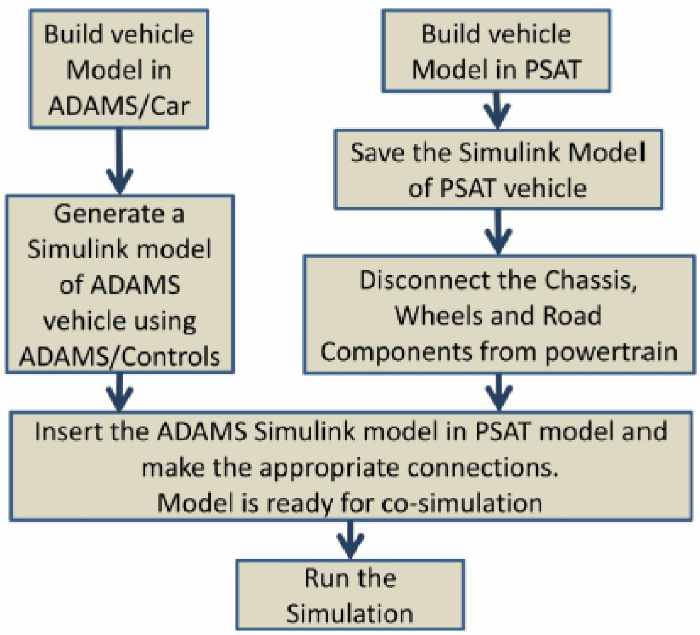


Figure 6 Flowchart for setting up co-simulation analysis (see online version for colours)

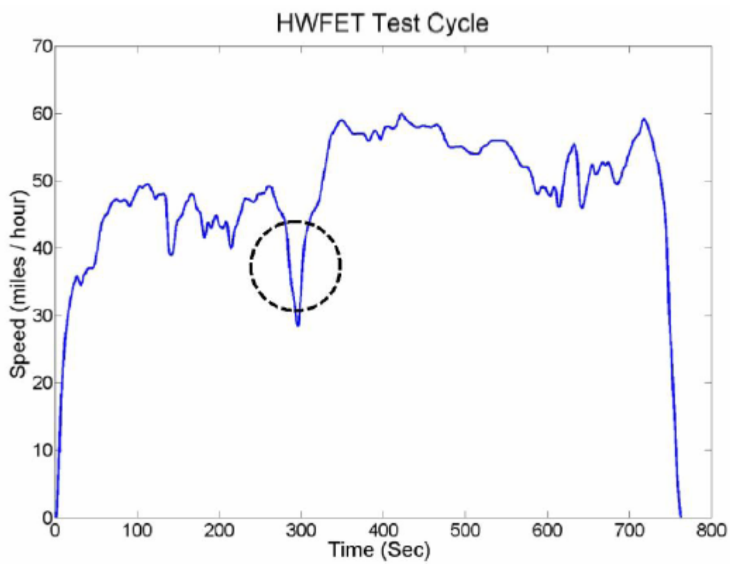


5 Co-simulation results

5.1 Effect of vehicle mass on the ability to achieve a velocity profile

The goal of this numerical experiment is to demonstrate the use of the co-simulation framework in capturing, under varying chassis inertias, the ability of a vehicle to meet a specified velocity profile. This simulation uses a model of a midsized sedan, with its chassis and unsprung mass represented in ADAMS, tyres modelled with FTire, and the engine/powertrain system represented with PSAT. The highway fuel economy cycle (HWFET), an emission test cycle developed by the US Environmental Protection Agency (EPA), was chosen as the target velocity profile for the vehicle. The HWFET cycle (US EPA, 2008), used for determining fuel economy of a light duty vehicle, is a high speed test averaging 48.26 miles/hour over 765 seconds with a peak speed of 59.9 miles/hour. The velocity map of the HWFET cycle is shown in Figure 7.

Figure 7 EPA's HWFET test cycle (see online version for colours)



The steep portions of this speed-time curve (for instance, the circled area of the velocity curve marked in Figure 7) represent, for a vehicle that is able to stay on this desired velocity profile, periods of high acceleration/braking. Hence, the mass of the vehicle has a direct impact on how closely it is able to meet the desired velocity profile while being driven by an engine of a given size. Note that this is typically the case for any vehicle, as its powertrain does not often change while the total mass of the vehicle does. A vehicle with very high mass cannot be suddenly accelerated/braked as it strongly resists any change in its momentum due to its higher inertia. For vehicles with high inertia, this leads to inability to closely follow the desired HWFET profile. The velocity profiles that were achieved by the vehicle with chassis masses of 450 kg, 1,600 kg, 2,000 kg, 2,500 kg, 3,000 kg and 4,000 kg are shown in Figures 8 to 13. It can be seen from Figure 13 that the vehicle with a sprung mass of 4000 kg is only barely able to match the desired HWFET profile shown in Figure 7. This behaviour is indeed expected due to the high inertia of the vehicle resulting in greater resistance to any sudden change in the velocity. In other words, the inertia of the vehicle imposes an upper limit on the maximum attainable acceleration for a vehicle with a given powertrain. Hence, velocity profiles of heavier vehicles progressively depart away from the specified HWFET test cycle.

Figure 8 Velocity profile achieved by a vehicle with chassis mass of 450 kg (see online version for colours)

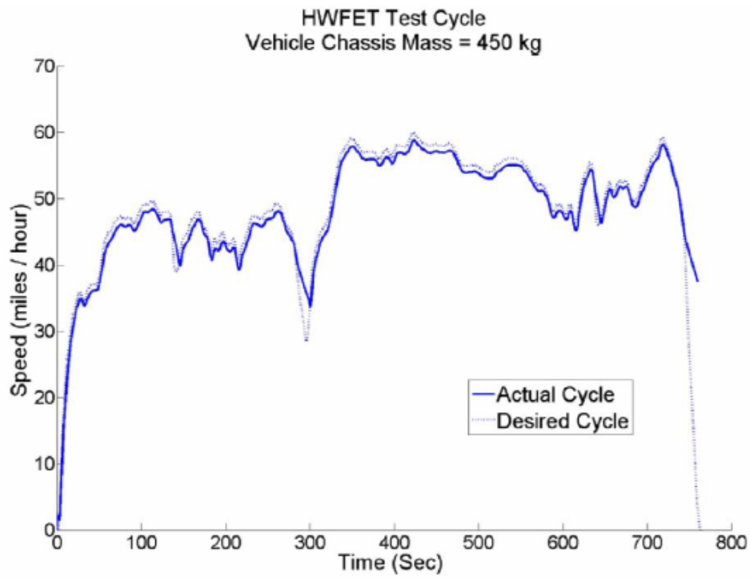


Figure 9 Velocity profile achieved by a vehicle with chassis mass of 1,600 kg (see online version for colours)

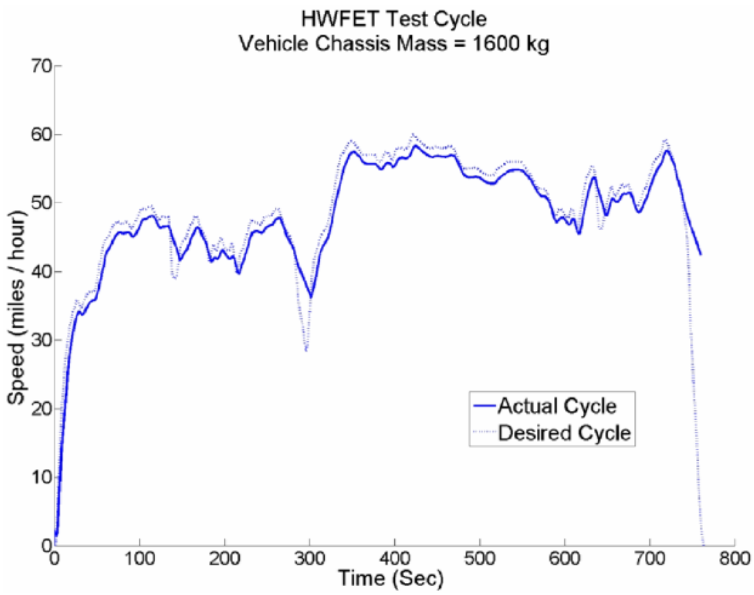


Figure 10 Velocity profile achieved by a vehicle with chassis mass of 2,000 kg (see online version for colours)

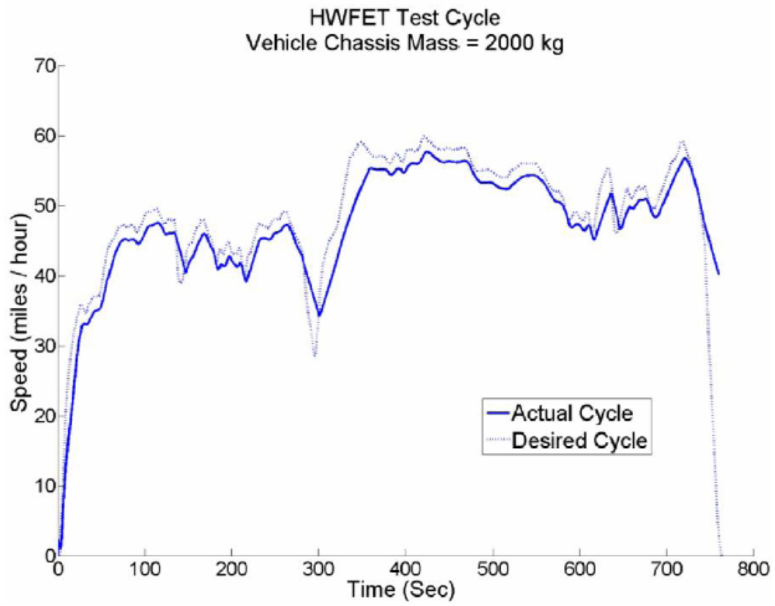


Figure 11 Velocity profile achieved by a vehicle with chassis mass of 2,500 kg (see online version for colours)

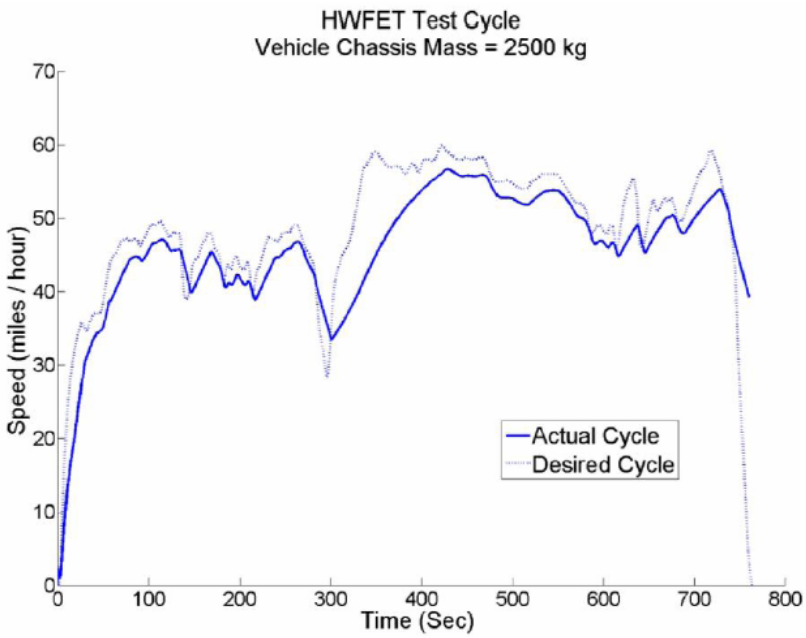


Figure 12 Velocity profile achieved by a vehicle with chassis mass of 3,000 kg (see online version for colours)

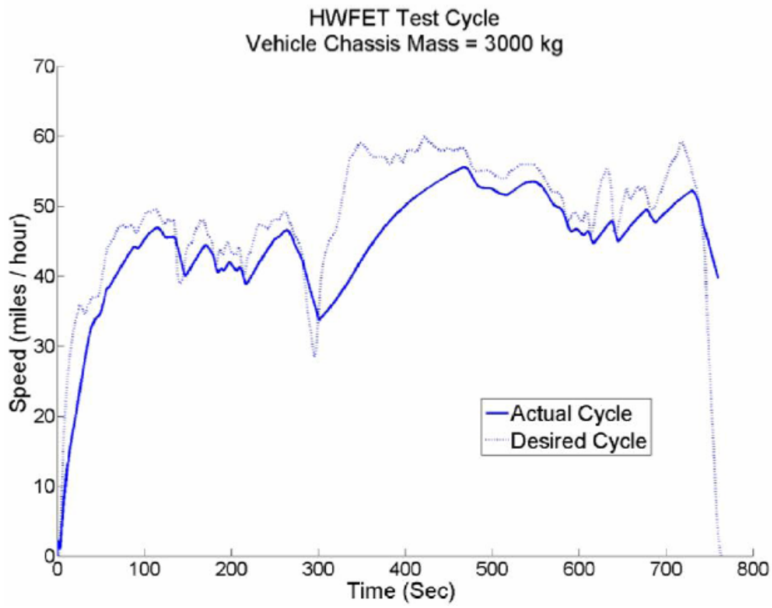
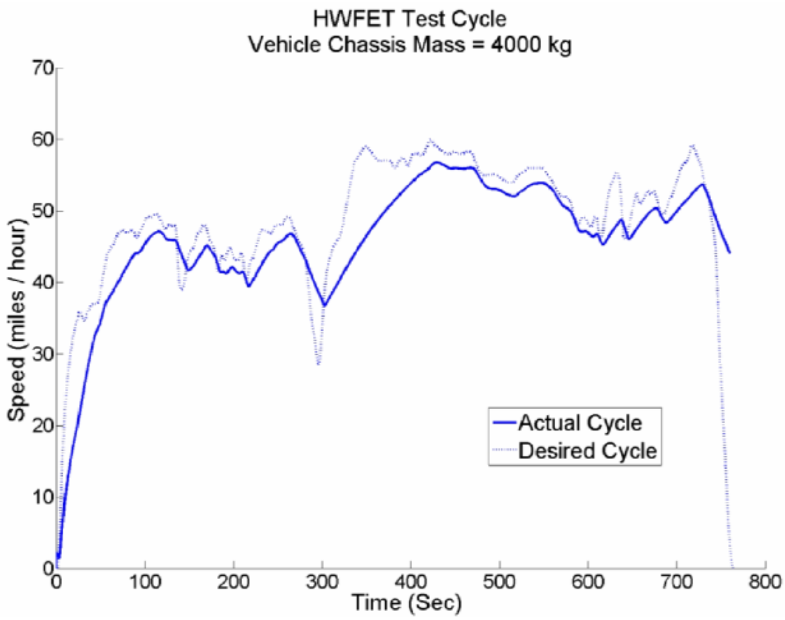


Figure 13 Velocity profile achieved by a vehicle with chassis mass of 4,000 kg (see online version for colours)



The velocity profiles for various chassis masses are all plotted together in Figure 14. One particularly steep portion of the HWFET cycle (marked by a rectangle on Figure 14), indicating high magnitudes of acceleration, is zoomed into to highlight the details (Figure 15). Recall that, the magnitude of maximum acceleration achieved by the vehicle is expected to decrease with an increase in the mass of the vehicle. This trend can indeed be observed for the set of simulations performed by varying the chassis mass and is plotted in Figure 16. The inability of heavier vehicles to closely match the specified HWFET profile is quantified by looking at the overall departure of the achieved profile from the specified profile. If the mean absolute error is higher, then the velocity profile is further away from the HWFET profile. Figure 17 shows variation in the mean absolute error with the increase in vehicle mass. It is clear from the plot that the mean error increases with the vehicle mass meaning that the vehicle's velocity profile, over the entire cycle, gets further away from the desired profile as the vehicle mass increases. The standard deviation of the error is shown in Figure 18 while the actual error value at every time step over the entire length of the cycle is shown in Figure 19.

One of the other attractive features of the co-simulation environment is its ability to capture the effect of vehicle dynamics on fuel economy. Any changes made to the vehicle model in terms of inertia properties, material models, subsystem types, etc., have an impact on the amount of fuel the engine consumes for a given drive cycle. For the design of experiments run with the HWFET cycle, the fuel economy for various chassis masses is shown in Figure 20. Here, the overall trend clearly suggests that as the mass of the vehicle increases, the fuel efficiency is reduced. This behaviour is indeed expected as the engine needs to do more work in order to move a vehicle with higher inertia. The apparent increase in the fuel economy for a vehicle with 4000 kg sprung mass is due to its attained velocity profile being much smoother than the HWFET cycle. This leads to the vehicle experiencing fewer fluctuations in the velocity, which ultimately leads to slightly better fuel economy.

Figure 14 Velocity profiles for vehicles with variable masses (see online version for colours)

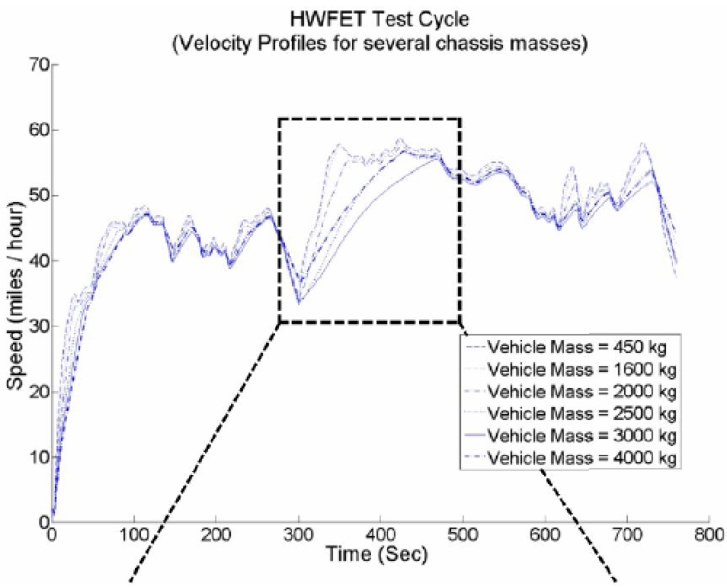


Figure 15 Velocity profiles for vehicles with variable masses (close up) (see online version for colours)

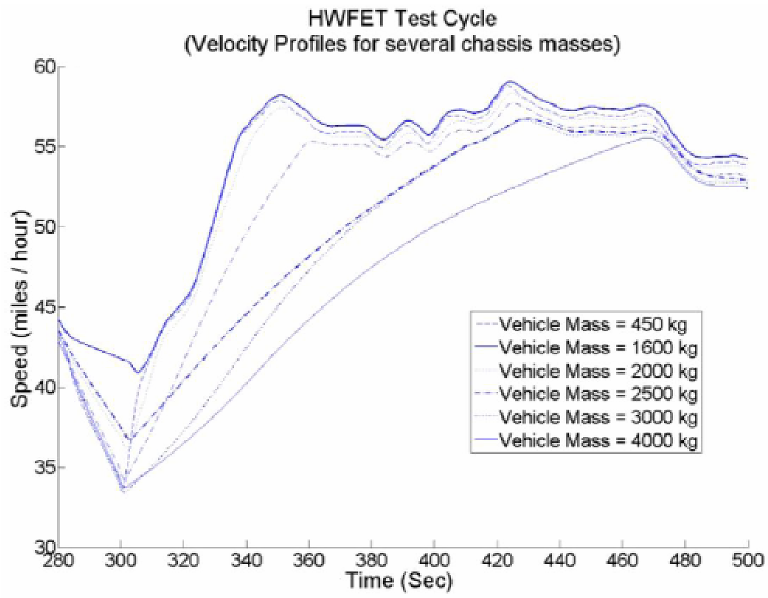


Figure 16 Variation in maximum vehicle acceleration with vehicle mass (see online version for colours)

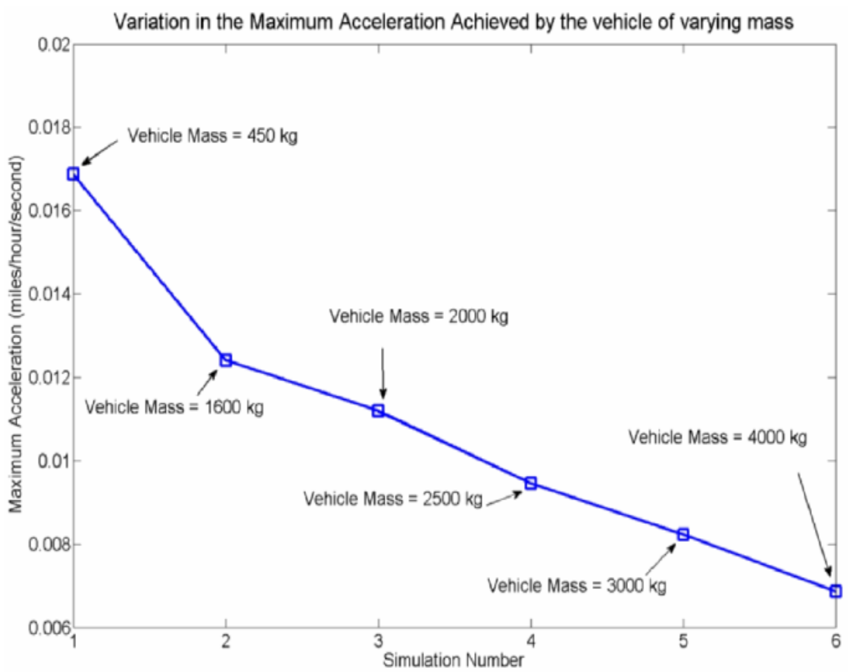


Figure 17 Variation of mean absolute error (see online version for colours)

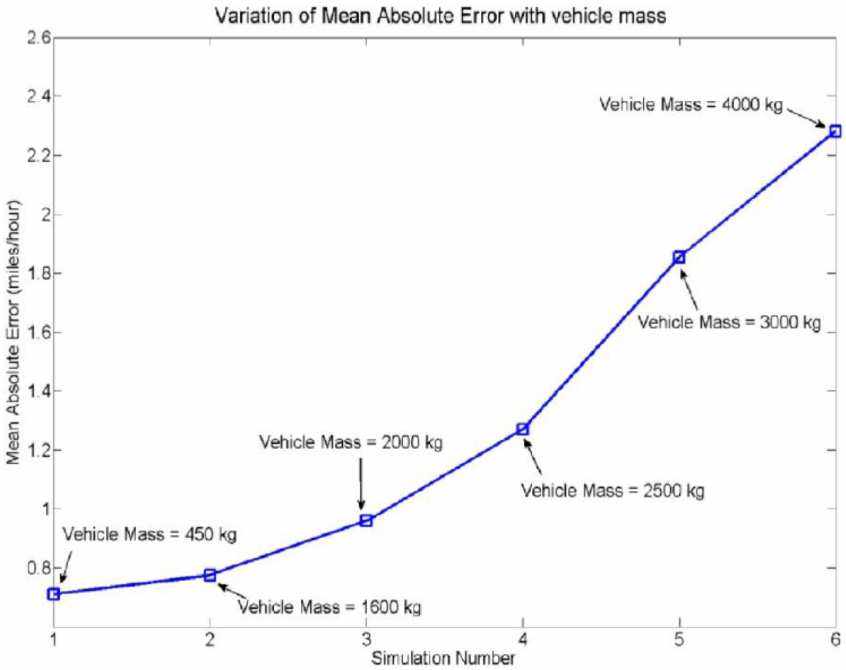


Figure 18 Variation of standard deviation of error (see online version for colours)

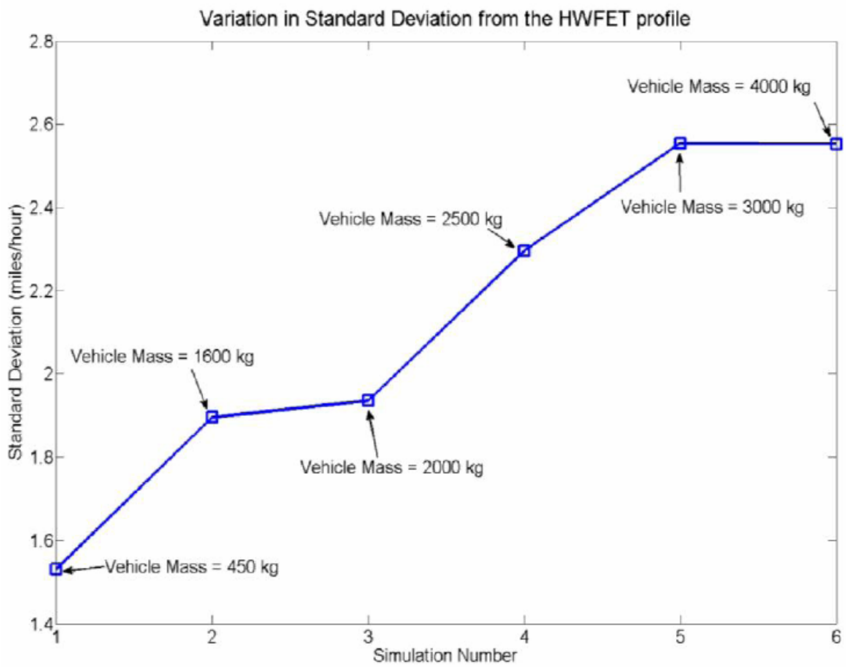


Figure 19 Variation in error over the cycle period (see online version for colours)

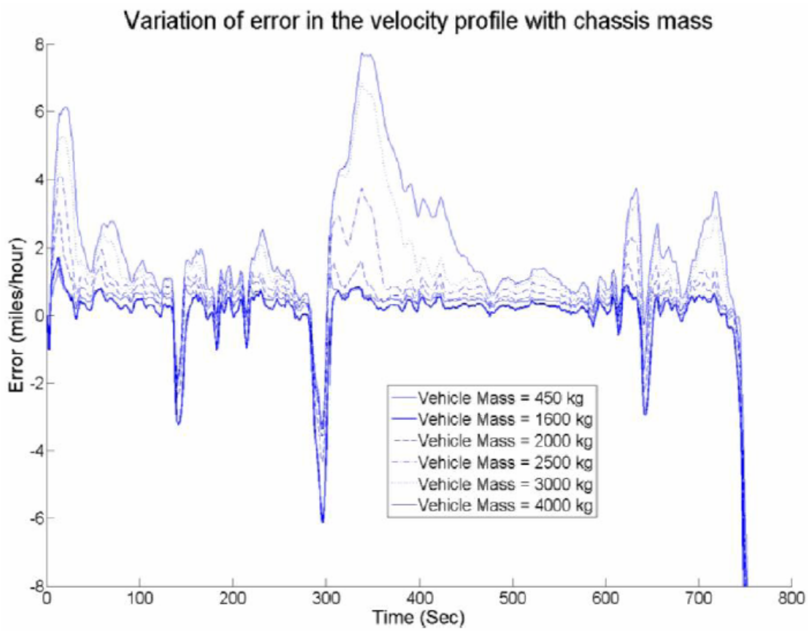
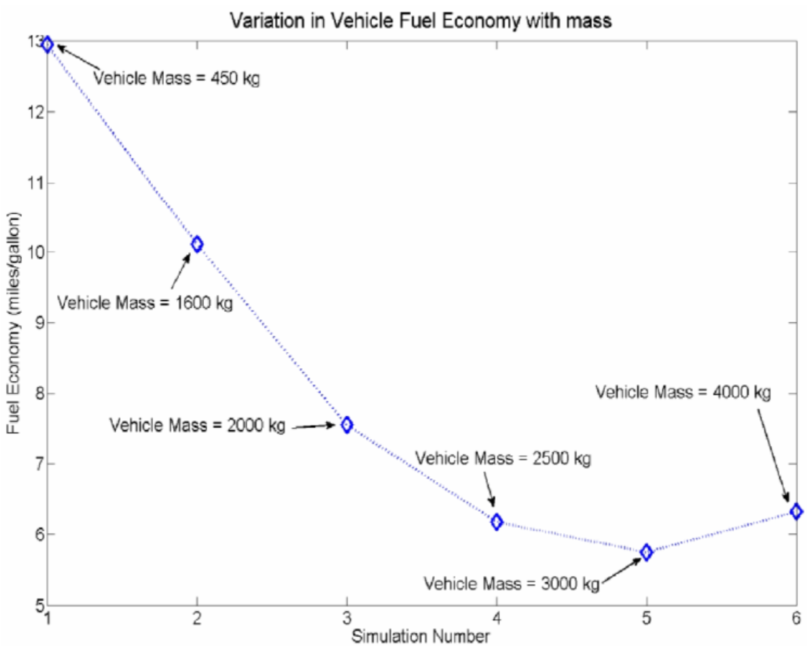


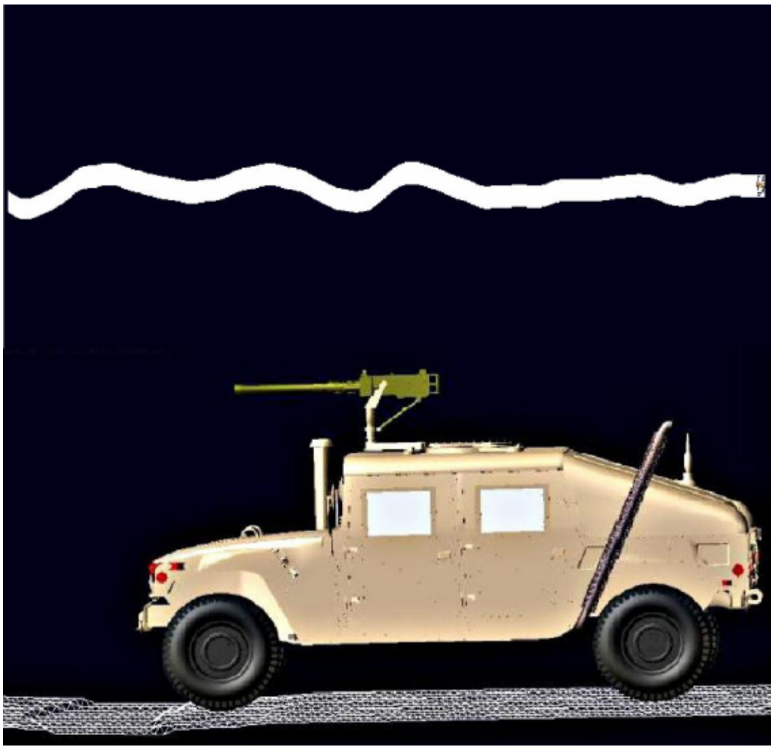
Figure 20 Variation in vehicle fuel economy with mass (see online version for colours)



5.2 *Off-road vehicle simulation*

The use of a co-simulation environment for understanding the performance of a midsize sedan given a particular powertrain setup was described in Section 5.1. The terrain considered for this simulation was flat and the vehicle always travelled in a straight line. This section describes a simulation that uses the co-simulation environment for a military vehicle travelling over an arbitrary three-dimensional terrain while negotiating turns at the same time. A driver model in ADAMS/Car controls the steering to make the vehicle follow the centreline of the road. A high fidelity of model of the US HMMWV is used for this simulation. The road profile (seen from above) and the vehicle (seen from the side) are shown in Figure 21.

Figure 21 Top: 3D road profile (top view), bottom: the HMMWV vehicle model (see online version for colours)

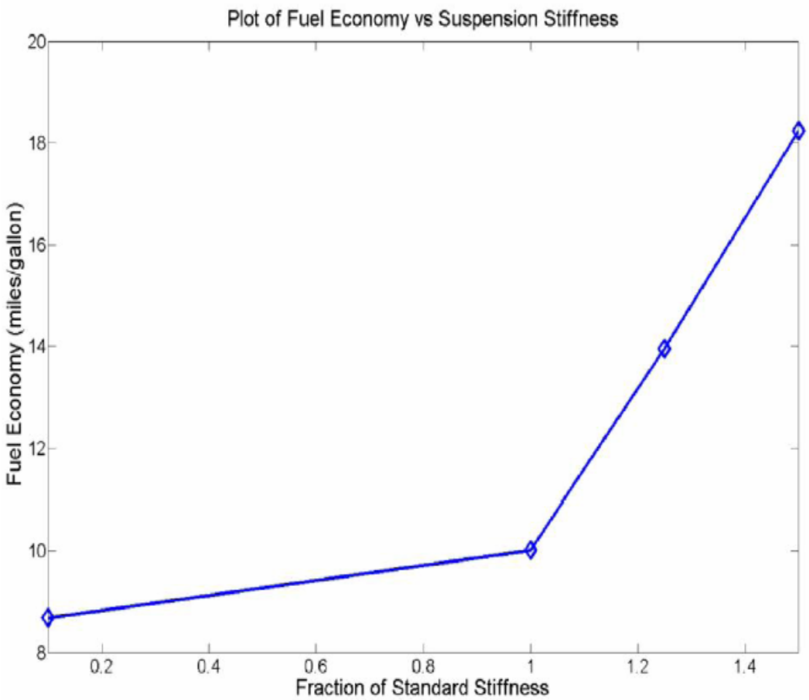


For this vehicle, the design of experiments is run with respect to the suspension parameters of the vehicle. Specifically, the effect of changing the suspension stiffness on the fuel economy of the vehicle is studied. The model of the suspension is shown in Figure 22.

The variation in the vehicle's fuel economy as a function of suspension stiffness is plotted in Figure 23. It can be seen that as the suspension stiffness is reduced, (spring stiffness and damping coefficient), the fuel economy is lowered as well. This can be attributed to a greater relative motion between the suspension components, resulting in a lesser fraction of engine effort being utilised to propel the vehicle forward. In other words, with a softer suspension, more energy is dissipated or is converted to potential energy.

Figure 22 HMMWV suspension (see online version for colours)

Figure 23 Fuel economy vs. suspension stiffness (see online version for colours)



6 Conclusions

This paper outlines a co-simulation environment that combines three packages to carry out high-fidelity analysis of vehicles. ADAMS is used to represent the vehicle chassis, suspension, steering and driver model to control steering. PSAT is used to simulate a variety of conventional, electric, hybrid, and fuel cell solutions to powertrain modelling along with a driver model to control the vehicle velocity. Finally, FTire is used to capture the tyre-road interaction. The co-simulation backbone is provided by MATLAB/Simulink. This vehicle co-simulation capability is used to demonstrate, using several analysis scenarios and vehicle types, its ability to simultaneously capture the interactions between the sprung/unsprung components, powertrain, and tyre, and hence understand the overall dynamics of the vehicle with high fidelity. All the details of setting up this co-simulation framework are provided in Datar and Negrut (2007). The models used for running the simulations are available for download, under the GNU public license (GPL) agreement, at http://sbel.wisc.edu.

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