

Vehicle Powertrain Test Bench Co-Simulation with a Moving Base Simulator Using a Pedal Robot

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ABSTRACT

To evaluate driver perception of a vehicle powertrain a moving base simulator is a well-established technique. We are connecting the moving base simulator Sim III, at the Swedish National Road and Transport Research Institute with a newly built chassis dynamometer at Vehicular Systems, Linköping University.

The purpose of the effort is to enhance fidelity of moving base simulators by letting drivers experience an actual powertrain. At the same time technicians are given a new tool for evaluating powertrain solutions in a controlled environment.

As a first step the vehicle model from the chassis dynamometer system has been implemented in Sim III. Interfacing software was developed and an optical fiber covering the physical distance of 500 m between the facilities is used to connect the systems. Further, a pedal robot has been developed that uses two linear actuators pressing the accelerator and brake pedals. The pedal robot uses feedback loops on accelerator position or brake cylinder pressure and is controlled via an UDP interface.

Results from running the complete setup showed expected functionality and we are successful in performing a driving mission based on real road topography data. Vehicle acceleration and general driving feel was perceived as realistic by the test subjects while braking still needs improvements. The pedal robot construction enables use of a large set of cars available on the market and except for mounting the brake pressure sensor the time to switch vehicle is approximately 30 minutes.

CITATION: Andersson, A., Nyberg, P., Sehammar, H. and Öberg, P., "Vehicle Powertrain Test Bench Co-Simulation with a Moving Base Simulator Using a Pedal Robot," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 6(1):2013, doi: 10.4271/2013-01-0410.

INTRODUCTION

One major part of any vehicle is the powertrain. This is what enables a vehicle to move forward providing energy conversion to torque at the wheels to overcome rolling resistance, aerodynamic drag and/or climbing resistance. The powertrain has also been under a lot of development recently as the environmental demands increase, [1]. To cope with the increasing demands the amount of hybrid vehicles using

multiple sources for energy have increased [1], [2]. This introduces several clever solutions providing good environmental performance at the cost of more complex and expensive systems. It is thus interesting to see how these solutions are perceived by a driver. Also, battery cost is a major issue for hybrid electric and plug-in hybrid electric vehicles and it is therefore interesting to see how the driver behavior influences battery lifetime, [3].

To improve the possibilities to evaluate driver perception of a vehicle powertrain one idea is to use a moving base simulation. In these situations the powertrain is usually simulated using a vehicle model. To enhance the fidelity of the powertrain one possibility is to use a hardware-in-the-loop, HIL, powertrain. This enables a driver in a moving base simulator to experience an actual powertrain and for technicians to try new powertrain solutions while letting a driver run a test in a controlled environment. There exists a lot of HIL setups which would benefit if they could be used cooperatively. Previous work has been done by [4] and [5] where an internet distributed setup with an engine was investigated.

In this work we have connected the moving base simulator, Sim III, at the Swedish Road and Transportation Research Institute, VTI, with the vehicle propulsion laboratory, presented in [6], at Linköping University, LiU.

Co-simulating a moving base simulator with a vehicle powertrain test bench using a test vehicle over a network connection is an area where little work has been done although individual parts have been well investigated. Therefore it's interesting to evaluate if this can be used to increase fidelity of current designs even further. The question we here initially investigate is if we think it is possible to obtain a realistic driving experience using a vehicle powertrain test bench in co-simulation with a moving base simulator.

EXPERIMENTAL SETUP

The main parts of the experimental setup are the vehicle propulsion laboratory at LiU, the moving base simulator Sim III, the pedal robot used to control the test vehicle in the propulsion laboratory, and the connection between the research facilities at LiU and VTI. In the following section these systems are all described. Further, the synchronization between the vehicle models and the driving mission used for the test driving is discussed.

Chassis Dynamometer Lab

A new chassis dynamometer lab has recently been built at the Division of Vehicular Systems, Linköping University [6], in the vehicle propulsion laboratory a chassis dynamometer setup is installed. The dynamometer provides four wheel motors/– generators that can provide both positive and negative torque at the wheels of a vehicle, and a control computer. This control computer can be given road profile data to simulate driving for an installed vehicle. An overview of the lab can be seen in [Figure 1](#).

System Description

The dynamometer units can operate as both motors and generators depending on the system mode and can thus both brake and propel the vehicle. The dynamometer units are mobile and can be moved to fit different vehicle sizes and configurations, such as 1WD (motorcycles), 2WD, or 4WD vehicles. The vehicle is fit to the dynamometers by removing

the driven wheels and mounting the vehicle to the dynamometer using adapter plates directly on the wheel hubs.

In a typical test setup the driver steps into the car as would be the case for a normal driving mission. In another scenario a pedal robot is used, e.g. when connected to an external system as discussed in this work. In both setups the experiments can be directed from the control room and the dynamometer can be controlled either through the Control PC or via CAN remote control which adds for extra safety because the external system can be used to automatically stop the dynamometer.

The outputs of the dynamometer are wheel torque and rotational speed but also vehicle speed and other quantities that can be calculated using the internal vehicle model. The torques are measured using string gauges fit to the drive suspension and the torque measurement accuracy is within 0.1% of measured value.

System Setup

Before starting an experiment a number of vehicle parameters is needed. Depending on operation mode they are

- Axle load in kg, m_a , and effective wheel radius, r_w , for calculation of safety limits
- Gear ratios, $r_{g,i}$, for all gears including the final drive, for calculation of engine speed
- Vehicle mass, m_v , front area, A_f , drag coefficient, c_d , and rolling resistance, c_r , for driving resistance calculation in the road force simulation mode
- Road topography map, including turn radii, for the road.

The chassis dynamometer equipment can be used in a variety of ways depending on the purpose of the experiments. One test mode is constant speed while measuring the torque exerted by the powertrain. In another test mode the forces a vehicle is exposed to during normal driving are simulated, e.g. used when simulating driving cycles. This is also the foundation for the road profile test mode that is used in this work.

Road Forces Simulation

The simulated forces that a vehicle has to overcome at the wheels are the aerodynamic drag force F_{air} , the rolling resistance, F_{roll} , the climbing resistance, F_{climb} , in case that the simulated road is not flat, i.e. has non-zero incline. The propulsion force at the wheels, F_{prop} , produced by the powertrain and the resistance forces determines the acceleration, a , of the mounted vehicle according to following model

$$F_{tot} = m_v \cdot a = F_{prop} - F_{res}$$

$$F_{prop} = \sum_i \frac{T_{w,i}}{r_w}$$

where m_v is the vehicle mass, F_{prop} the propulsion force calculated from the measured torque on each driven wheel.

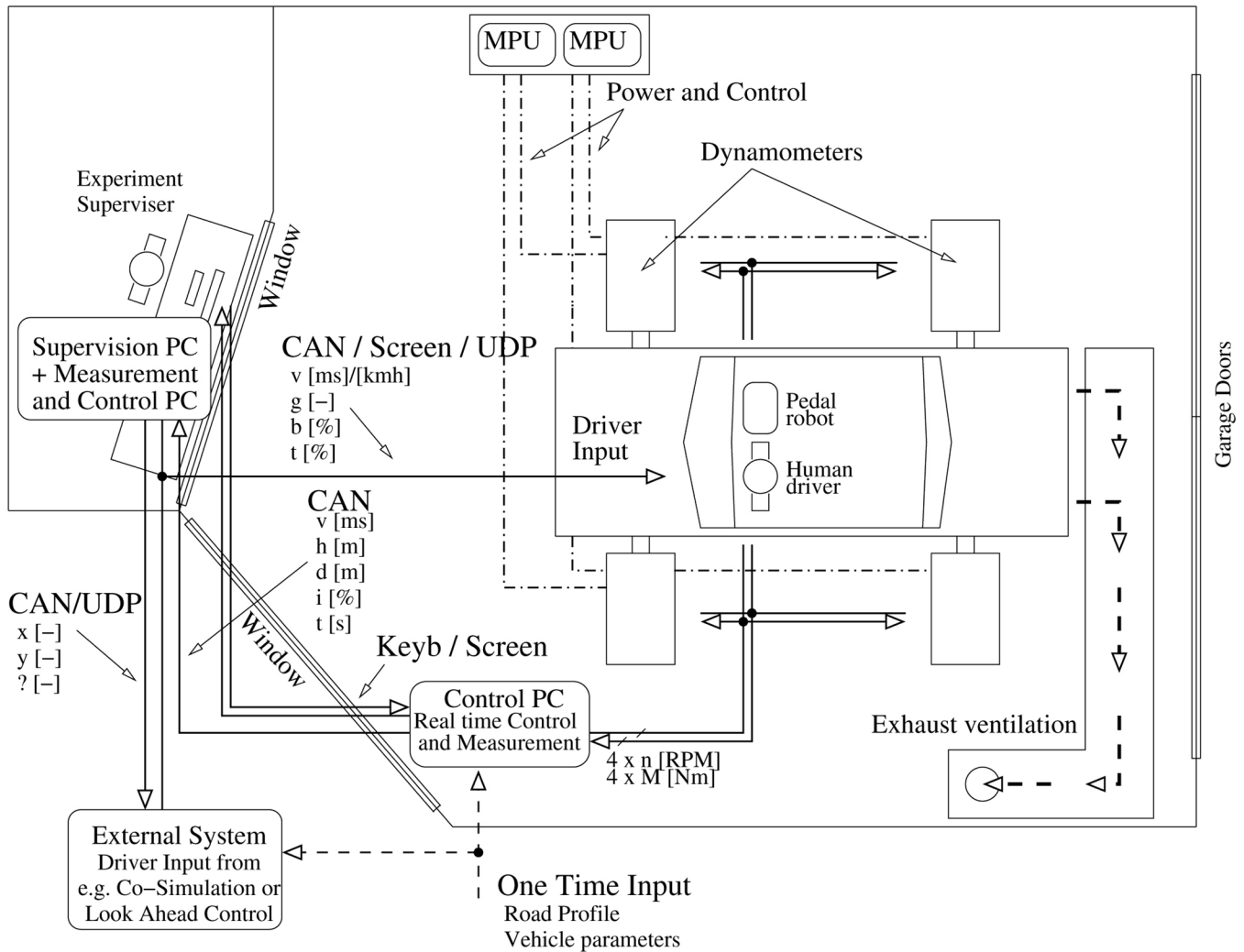


Figure 1. Schematic overview of the propulsion laboratory. The car is driven into the lab through the garage doors on the right and the dynamometers are then mounted to respective wheel hub. Road topography and vehicle parameters are then entered in the chassis dynamometer control PC. During the experiment the measurement and control PC in the control room forwards CAN messages from the chassis dynamometer to an external system via UDP. The external system then returns driver input to a human driver or, as in this case, a pedal robot.

$T_{w,i}$, and the measured wheel radius r_w which is constant during simulation. The resistance force F_{res} can either be a polynomial function in vehicle speed or a standard model for road resistance

$$\begin{aligned} F_{res} &= F_{roll} + F_{air} + F_{climb} \\ F_{roll} &= c_r \cdot m_v \cdot g \\ F_{air} &= c_d \cdot A_f \cdot \frac{\rho_{air} \cdot (v + v_0)^2}{2} \\ F_{climb} &= m_v \cdot g \cdot p \end{aligned} \quad (1)$$

where c_r is the rolling friction coefficient, g the gravitational acceleration constant, ρ_a the density of air, c_d aerodynamic resistance coefficient, A_f the frontal area of the vehicle, p incline of the road, and v_0 is the relative wind speed during

the experiment. In case a polynomial function is used the air drag and rolling resistance is replaced with

$$F_{air} + F_{roll} = c_0 + c_1 \cdot v + c_2 v^2 + c_3 \cdot v^3 + c_4 \cdot v^4.$$

Depending on the sign of $F_{prop} - F_{res}$ the simulated vehicle will thus accelerate or decelerate. If the incline is set to zero these equations will simulate driving on a flat road. The forces the vehicle has to overcome thus depends on the vehicle parameters and the velocity the simulated vehicle is traveling at.

Vehicle Dynamics Parameters

The parameters that are needed for the vehicle dynamics part when calculating braking force for the road simulation are

m_v - Mass of vehicle in kg

A_f - Front area m^2

c_d - Drag coefficient

c_r - Rolling coefficient

Built in parameters are

ρ_{air} - Air density (1.202 kg/ m^3 at an altitude of 200m)

g - Gravitational acceleration (9.81 m/s^2)

Test Vehicle

For this study a 2009 Volkswagen Passat Ecofuel DSG was used. This car has a dual clutch semi-automatic transmission and runs on both gasoline and methane. The maximal power of the car is 110 kW (150 hp) for both fuel options. In Figure 2 the car is shown mounted in the vehicle propulsion laboratory. Because it is a front-wheel driven car only the front wheels need to be connected.



Figure 2. The Volkswagen Passat that is used in the experiment mounted in the chassis dynamometer of the vehicle propulsion laboratory.

Before the experiments a brake pressure sensor was installed on the main brake cylinder. To be able to mount the pedal robot the driver chair was removed. The parameters that were used for the vehicle are listed in Table 1.

Table 1. Vehicle model parameters used in the study.

m_v	1 401	kg
c_d	0.320	-
A_f	2.0	m^2
c_r	0.01	-
r_w	0.3	m

Input and Output During Simulation

During simulation the input to the chassis dynamometer is those that a driver can give, namely

- Accelerator pedal position in the range [0 - 1].
- Brake pedal pressure, measured in the range [2.98 - 7] volts.

The outputs are in form of CAN messages sent either at 10 or 100 Hz. Status messages, such as temperature etc, are sent in 10Hz and simulation output messages are sent either at 10Hz or 100Hz. The outputs available through these CAN messages are summarized in Table 2

Table 2. Available output signals from the simulator rig.

Signal	Unit	Frequency	Description
n_i	[rpm]	100 Hz	Wheel speed
T_i	[Nm]	100 Hz	Wheel torque
v_l	[km/h]	10 Hz	Longitudinal vehicle speed
v_v	[km/h]	10 Hz	Vertical vehicle speed
r_{road}	[m]	10 Hz	Road curvature radius
H	[°]	10 Hz	Heading, relative origin
h	[m]	10 Hz	Elevation of road
p	[°]	10 Hz	Incline
d_{TP}	[m]	10 Hz	Distance since start
t_{TP}	[s]	10 Hz	Time since start
T_i	[°C]	10 Hz	Dynamometer temperature
$S_{d,i}$	[-]	10 Hz	Dynamometer status
S	[-]	10 Hz	System status

VTI Simulator III

The Swedish Road and Transportation Research Institute, VTI, is an independent research institute in the transport sector. The principal task of VTI is to conduct research and development related to infrastructure, traffic and transport. The institute has technically advanced equipment, and part of this equipment are the driving simulators. For this work, particularly the advanced moving base simulator, VTI Simulator III, or Sim III was used.

Sim III uses state of the art techniques for simulation of road conditions [7] and has earlier been used in, amongst others, studies related to effects of yaw stability at side impact [8]. A picture of Sim III can be seen in Figure 3.



Figure 3. The moving base driving simulator Sim III at VTI.

The linear motion system of Sim III's has four degrees of freedom and offers both linear and tilt motion at an acceleration of 8 m/s^2 . Realistic lateral motions are obtained