

Longitudinal Vehicle Dynamics Modeling and Parameter Estimation for Plug-in Hybrid Electric Vehicle

Sindhura Buggaveeti, Mohit Batra, John McPhee, and Nasser Azad
University of Waterloo

ABSTRACT

System identification is an important aspect in model-based control design which is proven to be a cost-effective and time saving approach to improve the performance of hybrid electric vehicles (HEVs). This study focuses on modeling and parameter estimation of the longitudinal vehicle dynamics for Toyota Prius Plug-in Hybrid (PHEV) with power-split architecture. This model is needed to develop and evaluate various controllers, such as energy management system, adaptive cruise control, traction and driveline oscillation control. Particular emphasis is given to the driveline oscillations caused due to low damping present in PHEVs by incorporating flexibility in the half shaft and time lag in the tire model. Accurate and reliable vehicle dynamics parameters that control the vehicle motion are estimated by acquiring experimental data from longitudinal maneuvers of the PHEV equipped with a vehicle measurement system (VMS), global positioning system (GPS) and inertial measurement unit (IMU). The simulated model with estimated parameters is analyzed for longitudinal dynamics by comparing with experimental data from on-road testing.

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INTRODUCTION

Over the past few years, the automotive industry has witnessed a major shift from conventional vehicles (CV) to plug-in hybrid electric vehicles and battery electric vehicles (BEV) to address the growing concern for gasoline prices and carbon pollution. Although EVs have demonstrated significant energy efficiency over CVs, limited driving range, higher upfront costs and limited availability of public charging stations made PHEVs a viable option over EVs for the short term. PHEVs are equipped with complex power train architecture and use advanced control strategies to improve their performance which led the automotive industry to research solutions to reduce the development procedure.

Model-based control design is proven to be a time-saving and cost effective approach that allows the designer to move directly from model creation to simulation, code generation and hardware-in-the-loop (HIL) test in a systematic fashion. It enables the designer to optimize and validate the controllers before deploying on hardware platform. Model based design of trip planning module, energy management system(EMS) and adaptive cruise control system whose ultimate goal is to improve fuel efficiency of Prius PHEV requires a longitudinal dynamics model of the vehicle which is an important degree of freedom for assessing fuel consumption [1]. In addition, power-split HEVs are prone to lower damping in the driveline due to the absence of clutch or torque converter [2] making it necessary to have a vehicle model that could be used in implementing and evaluating driveline oscillations controller. The developed model has

to be specified with accurate parameters to replicate the real vehicle behavior, making system identification a crucial part in model based control design.

Advanced test facilities such as vehicle inertia measurement rigs, wind tunnels, drum testing machines and 8-post rigs are capable of estimating location of vehicle center of gravity, drag coefficient, tire and suspension parameters respectively with high accuracy. For example, Vehicle Inertia Measurement Facility (VIMF) [3], commonly used by automotive manufacturers could measure center of gravity height with an accuracy of 0.5%. However, utilizing these facilities is not always feasible for research purposes and requires skilled technicians to conduct tests. Also, tire parameters that are determined through tire test rig and adapted to real road conditions requires relevant expertise of the user and compromise on the fact that the results of drum testing can differ significantly from the behavior of real tire on the track.

Therefore, this paper focuses on identification of parameters of Prius PHEV through the data collected from real road driving maneuvers. Data is acquired from a vehicle measurement system (VMS) developed by AnD Technology [4] that includes embedded controllers and high-accuracy sensors. It also comes with on-board filters that remove high frequency noise from the recorded data, thereby reducing the need to use additional filters during the estimation process. This paper presents improved estimation methods over a similar work done on an EV[5].

TEST VEHICLE

The test vehicle chosen is the Toyota Prius Plug-in Hybrid with front engine, two axles and front wheel drive (FWD) layout. Detailed tests were conducted on the Prius at Toyota Motor Manufacturing Canada (TMMC) test tracks. Data was recorded by integrating the measurements from a system of sensors using VMS manufactured by AnD, GPS and IMU. Fig. 1 shows each of the four wheels fitted with sensing equipment. The sensor set mounted on each of the wheels collates required data to measure vehicle parameters from a group of five sensors listed in Table 1.

While the GPS was used to record vehicle speed and acceleration, the triggers for acceleration and braking are recorded in order to evaluate the vehicle response during longitudinal maneuvers. The data recorded by VMS, GPS and IMU was integrated with the help of an integration device from ‘Vector Informatik GmbH’ so as to have a common time stamp for the collected data. Few sets of measurements from VMS, GPS and IMU are compared to cross validate the correctness of data. The system architecture for integrating the three devices using the Vector is shown in Fig. 2.



Figure 1. Prius fitted with VMS

Table 1. List of sensors in vehicle measurement system (VMS)

No.	Sensors in VMS	Measurement
1	Wheel force sensor	Wheel force and moments in x,y,z directions along the co-ordinate axes fixed to tires
2	Rotary encoder	Angular speed of wheel
3	Laser ground sensor	Pitch, camber, yaw and effective radius of wheel
4	Laser Doppler velocimeter	Wheel translational speed
5	Wheel position sensor	Position of wheel with respect to a reference point fixed on the vehicle

Coast down tests, acceleration and braking tests that excite the vehicle in longitudinal direction, and speed bump tests that excite the vehicle in vertical direction were done for the parameter estimation of the vehicle dynamics model.

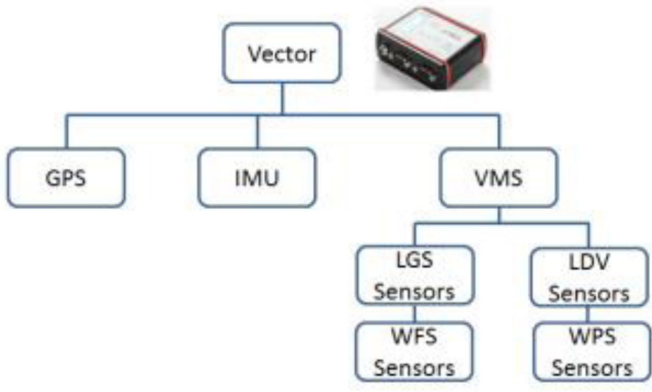


Figure 2. System architecture for data collection

Longitudinal Vehicle Dynamics Model

Forces acting on the vehicle during longitudinal motion are shown in Fig. 3. The dynamic equation for the longitudinal motion of the vehicle is:

$$M\ddot{x} = F_{xf} + F_{xr} - F_{rf} - F_{rr} - F_d \tag{1}$$

where F_{xf} and F_{xr} are the longitudinal traction/braking forces acting on the front and rear wheels, F_{rf} and F_{rr} are rolling resistance forces on the front and rear wheels and F_d is the aerodynamic drag on the vehicle acting at center of pressure (CP) located at a height of h_d from ground. Also F_{zf} is the sum of normal forces on the front left and right wheels and F_{zr} is the sum of normal forces on the rear left and right wheels. The location of CG from the front and rear wheels is l_f and l_r respectively, the height of the CG is indicated by h , and mass of the vehicle is represented by M .

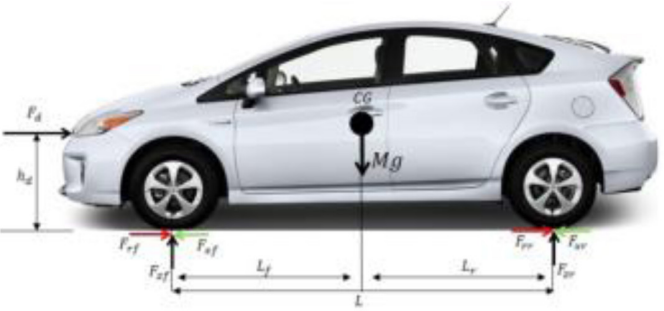


Figure 3. Forces acting in longitudinal direction on Prius PHEV

MapleSim Model

The vehicle dynamics model of Toyota Prius PHEV is developed in MapleSim due to its symbolic calculation and optimized code generation capability which makes the model very suitable for HIL and model-in-the-loop (MIL) tests. The model consists of 18 degrees of freedom (DOF) with chassis modeled as 6DOF rigid body, 4DOF from suspensions, 4DOF from wheels and another 4DOF from torsional deformation of the half shaft. Fig. 4 shows the three dimensional representation of longitudinal vehicle dynamics model in MapleSim.

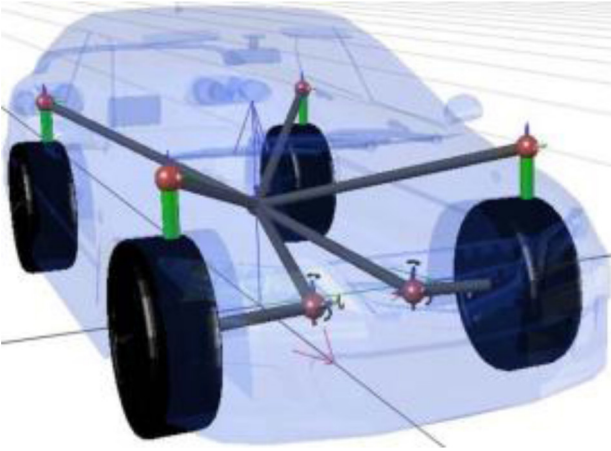


Figure 4. Chassis model of Prius PHEV in MapleSim

Table 2. Few parameters of MapleSim model: Prius PHEV

Parameter	Symbol	Value	Units
Mass of car (measured)	M	1631	kg
Wheel base (specified)	L	2.66	m
Track length (specified)	w	1.745	m
Frontal area (estimated)	A_f	2.2075	m^2
Coefficient of drag (specified)	C_d	0.25	-
Rolling resistance coefficient (estimated)	μ	0.014	-
Height of CG (estimated)	h	0.61	m
Longitudinal location of CG from rear (estimated)	L_r	1.45	m
Wheel inertia (estimated)	J_w	1.67	kgm^2
Torsional Stiffness of the left and right half shaft (estimated)	k_{hs}	29292.503 and 16576.225	Nm/rad

The model consists of a rigid body connected to tires through four suspensions. One end of the half shaft is connected to the wheel while the other end is connected to the car body through universal joints. This configuration ensures that drive train components are mounted on the chassis. Flexibility is introduced in the half shaft by modeling it as a torsional spring, damper and mass system. Pacejka tire model is used in the vehicle dynamics model due to its advantages over other tire models [6]. Suspensions are modeled as four vertical springs in order to maintain the simplicity of the longitudinal vehicle dynamics model.

The model accepts motor torque as a model input and half-shaft torque, vehicle speed, wheel speed and jerk are the model outputs. All parameters identified based on experimental testing of Prius PHEV are specified in Table 2.

PARAMETER ESTIMATION

MapleSim model should be supplied with accurate parameters for vehicle dynamic simulation. A few parameters such as wheelbase, front and rear track widths can be measured directly. However, these are insufficient to describe the vehicle longitudinal motion. More calculations are necessary to compute the vehicle parameters such as:

Frontal area
Rolling resistance coefficient
Center of gravity location
Suspension stiffness and damping
Wheel inertia
Tire model coefficients
Half shaft stiffness

In this section, the methods used to calculate the vehicle parameters are discussed. A MATLAB/Simulink based non-linear least squares estimator [7] is chosen for parameter identification.

Frontal Area Estimation

Frontal area of a vehicle is defined by the Environmental Protection Agency (EPA) as, “the area of the orthogonal projection of the vehicle on a plane perpendicular to the longitudinal axis of vehicle”. It is an important parameter used in the estimation of drag force acting on a vehicle. At first, the frontal image of Prius PHEV was processed to fill the region of the car with black and the back ground with white color [8]. Then ‘im2bw’ function in MATLAB is used to convert the grey scale image to binary image which outputs an image as shown in Fig. 5 in which black pixels are replaced with the value 0 and white pixels are replaced by value 1. Percentage of area with black pixels is determined and scaled back to the actual size of Prius which gives the frontal area of the Prius as $2.19m^2$ which is 84.2% of the total area of the box ($2.60m^2$).



Figure 5. Frontal image of Prius PHEV in B and W.