

Predictive Transmission Shift Schedule for Improving Fuel Economy and Drivability Using Electronic Horizon

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ABSTRACT

This paper proposes an approach that uses the road preview data to optimize a shift schedule for a vehicle equipped with an automatic transmission. The road preview is inferred here from the so-called electronic horizon of a digital map that includes road attributes such as road grade, curvature, segment speed limit, functional class, etc. The optimized shift schedule selects the gear ratio whose optimization is conducted through applying a hybrid model predictive control method to the powertrain system, which is modelled as the multiple plants associated with multiple gears together with engine models. The goal of this optimization of shift schedule includes improving real world fuel economy and drivability. The real-world fuel economy gains using the proposed approach are achieved through optimizing gear ratio w.r.t. the road grade variations of the road ahead. The drivability improvement focuses on enhancing a driver's curve negotiation performance through eliminating back-to-back shifting that can cause shift business. The proposed strategy is verified in a simulation environment, which integrates the vehicle model architecture for powertrain systems (VMAPS), the vehicle dynamics simulation package, and the road preview model. The simulation results showed the effectiveness of the proposed predictive shift strategy in achieving the desired goal.

CITATION: Lu, J., Hong, S., Sullivan, J., Hu, G. et al., "Predictive Transmission Shift Schedule for Improving Fuel Economy and Drivability Using Electronic Horizon," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-1092.

1. INTRODUCTION

Road preview info is currently getting into automotive production applications due to the implementation of many ADAS (advanced driver assistance system) features and vehicle convenience features. Future self-driving cars are significantly expanding the capability of the current road preview and can provide even higher fidelity preview data due to the implementation of much more powerful perception sensors such as camera, Lidar, radar, and their fusions.

While the perception technology is progressing at an incredible pace for ADAS systems and for autonomous vehicles, its adaptation to the other applications such as the traditional powertrain and chassis controls are generally at a much slower pace. The development of autonomous vehicles is demanding further speeding up the advancement of the perception technology and the gap between what are available and what have been applied (outside traditional ADAS) is likely to continue increasing.

Exploring and implementing preview based vehicle features are likely to carry both long and short term benefits. Instead of waiting for a perception system to become a commodity before road preview adaptation, many auto OEMs and suppliers are now start to pay attention to what are currently available. Those currently available technologies include vehicle navigation/digital map [1], vehicle-to-

vehicle communication [2], vehicle-to-infrastructure communication [3], vehicle-to-cloud communication [4], and forward collision radar/camera based [5].

Recently, the road preview for powertrain controls has been implemented in several commercial vehicles, for example, RunSmart predictive cruise control from Freightliner Trucks [6] and predictive powertrain control from Daimler [7] use road preview from digital maps to detect road grades ahead and to adjust their cruise controls in a way that can deliver the most fuel-efficient powertrain performance. For passenger cars, Rolls-Royce Satellite Aided Transmission uses GPS data to anticipate the driver's next move based on location. It then selects the most appropriate gear for the road ahead, making for a smoother driving experience [8]. [9] provides another approach which uses predictive gearshift strategy for fuel economy improvement.

In this paper, we explore a similar setup by using road preview from Electronic Horizon (EH) of a digital map to further enhance the real-world fuel economy and drivability. The EH is a GPS location based digital map which include rich road attributes info. While our goal is the same as those in [6, 7, 8, 9], we take a different approach, namely, we explore using a multi-model based model predictive controller (MPC) to optimally determine the gear ratios w.r.t. the previewed road grade, curvature, and speed limit. This approach models the powertrain system as a plant with multiple modes each of which is associated with a given gear ratio. The real-world fuel

economy gain by this approach is achieved through optimizing gear ratios w.r.t. the grade variations of the road ahead. The drivability improvement focuses on enhancing a driver's curve negotiation performance by eliminating back-to-back shifting which can potentially lead to the shift business. The proposed predictive strategy has been verified in a simulation environment that integrates the vehicle model architecture for powertrain systems (VMAPS), the vehicle dynamics simulation package, and the road preview model.

The paper is organized as follows: Section 2 provides a review of the electronic horizon and a look into some of the real vehicle EH data from SYNC Gen 3 in a 2013 Lincoln MKS, which was taken on various data-collection travels from Michigan to Ohio, and to West Virginia. The next section, we focus our attention on the powertrain modeling which is relevant to the plant used for the control design. In section 4, a discussion on model predictive control (MPC) is provided. Section 5 focuses on road-grade preview based shift optimization for real-world fuel economy. Section 6 is devoted to the shift schedule optimization for improving drivability for driving on curved roads. Section 7 concludes the paper.

2. ROAD PREVIEW USING EH

Digital maps have found many applications nowadays ranging from a 2D map for turn-by-turn navigation to a high fidelity 3D map for self-driving cars. Although most of the 2D digital maps are only used for navigation purposes, limited 3D road data can be embedded into the 2D digital Map. Such 3D enhancements to the traditional 2D digital map can be added to the 2D digital map without high cost.

One of such enhancements is the so-called Electronic Horizon (EH), which can anticipate the road ahead, effectively expand the driver's horizon beyond what is immediately visible, and thus provide valuable preview information on the road horizon ahead. The EH was originally proposed as a feature for safe driving, which falls under the label of advanced driver assistance systems (ADAS) [10].

Most EH applications use road data conforming to the ADASIS V2 (Advanced Driver Assistance Systems Interface Specifications) [11] specification. Those systems deliver data over the vehicle's CAN network in a standardized packet format that can be decoded by as many consuming users as needed. One device in the system, typically integrated with the navigation and/or infotainment systems in the vehicle, acts as the EH data provider. Using GPS location, and preferably information about the desired or most probable path, the provider device extracts road preview information from the map database for a pre-determined amount of preview distance. This data is transmitted on the CAN bus whenever there is updated information about the road ahead.

Due to the fact that the vehicle needs to be positioned in the 2D digital map with EH enhancement, localizing the host vehicle on the digital map is critical. This localization is currently conducted through Global Positioning System (GPS). Hence the availability of GPS signals determines where EH based features can be deployed. For this purpose, [12] conducts an analysis of GPS availability, from the perspective of dilution of precision (DOP) and number of satellites in view, through data collected from 13,000 km US test

vehicle drive comprising real world driving profile of freeways, rural, urban, and residential roads. The test results showed that a GPS position solution was possible (at least 4 satellites in view) in 96% of the dataset. The GPS outage duration for the time that fewer than 4 satellites were in view was 19 seconds. These results were aggregated across the entire dataset, which represents typical driving patterns in the U.S. Therefore, [12] confirms that availability of the high quality GPS signals in US roadways and with short GPS outage durations.

Besides the GPS availability in roadways, the next question is EH data coverage. Typical information from EH CAN packets includes road grade and curvature, effective speed limit, vehicle position, vehicle travel speed, lane information, function class of the road, etc. Various other information about the road may be provided as well, including road type, road sign, data about branch intersections, etc. The content depends on operating conditions, age of the map database, and the decisions used in the implementation of the data provider. Typically, road grade and curvature data are available for highways and most thoroughfares. Smaller roads generally have much less road attribute data available. The amount of available data usually improves with each update of the map database from the digital map providers.

A reconstructor is used to decode and interpret the EH's CAN data stream, which generate the data that can be used by each consuming electronic control unit (ECU) or a standalone device. The data reconstruction is usually performed by a software component, which could be hosted in the consuming ECU or another hardware device such as a multi-media or telematics module. For the current development, a rapid-prototyping system of dSpace autobox is used to host the EH data reconstruction computation. The reconstructions are typically developed for each specific end-user, as they need to be customized, for efficiency, to extract only the desired information and maintain only the necessary preview depth to minimize memory and computation consumption. Therefore, reconstructors are generally not shared by different applications, but the algorithms can be shared for extracting customized EH data.

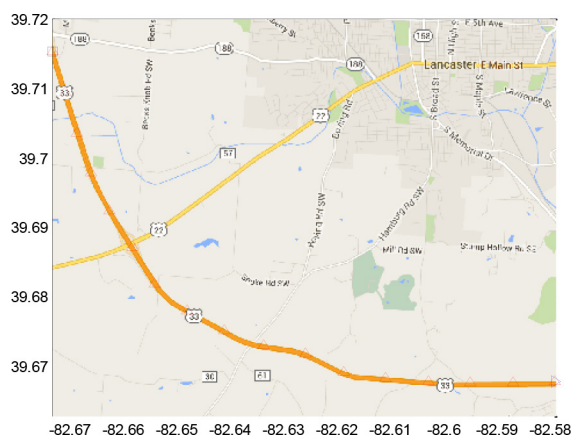


Figure 1. An example route used to collect EH data

In a similar fashion, we have created a reconstructor that can convert the EH CAN message from a microprocessor inside SYNC Gen 3, where digital map with EH capability is hosted. The reconstructed road attribute data from the EH CAN messages are then integrated

with a simulation platform including VMAPS, vehicle dynamics, and road constructor to enable a software-in-the-loop testing environment that is used for the road preview based feature development. This is a rather critical step for simulating, evaluating, and verifying the current predictive shift scheduling and for the other predictive powertrain and chassis control applications.

While the fuel economy and drivability benefits for the current approach to use EH data for shift scheduling can be hard to quantify using on-road testing due to the fact that the on-road driving is constrained by the traffic conditions, they can be easily quantified in the aforementioned software-in-the-loop simulation environment. Also such benefits often do not show up on the drive-cycle testing like they would in real-world conditions, hence incorporating the real-world road condition through EH in the simulation environment is useful.

Previewing what is about to happen next is invaluable for optimizing many aspects of powertrain and chassis controls. Its application can likely generate benefit beyond what the current ADAS applications are implemented for. Grade and curvature are probably the most critical road attributes for fuel economy and drivability. Having access to other on-board vehicle signals and fusing those additional signals with EH data likely provide more reliable and robust prediction of the road ahead. For example, steering wheel angle, pedal position, turn signal, navigation route, route history, etc. all help to provide a more accurate picture of the upcoming road and the upcoming intent of the driver that can be used to better optimize comfort and fuel consumption. As additional sensing systems come online, such as radar, Lidar, vision systems, etc., we have even more ways to preview roads to improve the overall robust prediction of the driving scenario.

It is also a good practice to include a confidence factor along with the interpreted preview information for the final, compensated or conditioned data. A high-confidence factor should be closely adhered to the consuming applications, while a low confidence prediction may be weighted or ignored as appropriate. Confidence factor may be determined from the quality/density of map data in the region, quality of GPS signals, type of signals being used, or any number of other factors.

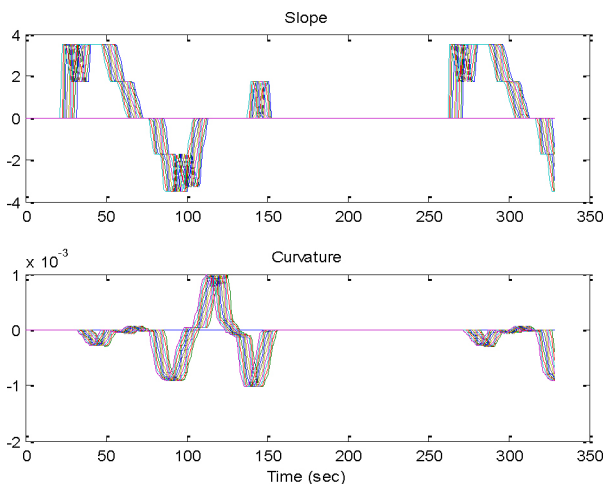


Figure 2. The road grade and curvature preview data (EH) from the route shown in Figure 1

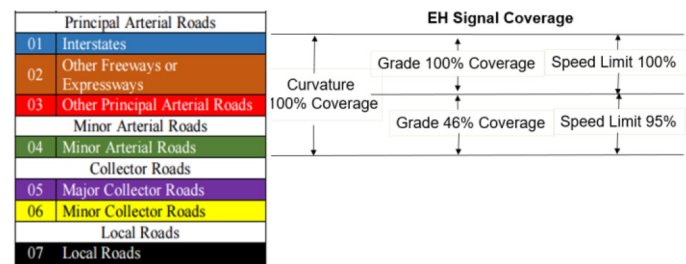


Figure 3. Road attribute coverage from EH database for different road function class

As an example, Figure 1 shows a test route where we collect EH data for EH data quality study. Figure 2 shows the preview road grade and curvature reconstructed from SYNC Gen 3 EH data and the data was sent reconstructed every 1 second ahead up to 10 sends. Not all the road attributes are fully covered by the current EH database for all the road surfaces. For example, Figure 3 shows that the EH covers curvature for all the road surface in US; while it covers the road grade for 100% roads of function class 1 and 2, it only covers 46% for roads of function class 3 and 4; EH covers the speed limits for 100% of roads with function class 1 and 2. Hence, generally speaking, EH based predictive features can be robustly implemented for features which are useful for high way driving scenarios. Due to the EH's road curvature data covering 100% of the roads, curvature related features can be robustly implemented,

To optimize the predicative shift strategy, two methods were proposed through fusing EH data and the other on-board sensor measurements. The first method uses EH data captured through the ADAS Research Platform (ADASRP) (from HERE). This tool allows the generation and capture of ADASIS CAN messages from a simulated drive. However, for more realistic ADASIS data, actual ADASIS CAN messages were captured on a vehicle equipped with production intent EH system in SYNC Gen 3.

The EH data includes current vehicle speed, position along the path and the future road grade, curvature associated with the path, etc. From this data set a second-by-second vehicle speed, road grade and curvature map are created. They are then fed into a software module or reconstructor that decodes the EH CAN packets into engineering variables that can be used as the inputs to a sensing module to the condition/fuse/compensate road preview dat. This final road preview data is then fed into the controller which is scheduling the shift. In the aforementioned simulation environment, vehicle model receiving the gear shift commands contains plant models of the powertrain, chassis systems, and the environment.

3. MPC

When the powertrain control sees an uphill ahead, it can adapt to the future road changes in order to help improve fuel consumption. For instance, if the powertrain control increases the vehicle speed prior to negotiate the uphill, it is likely to avoid unnecessary fuel consumption or downshifts due to reacting to excessive power demand or acceleration intent. Furthermore, when traveling on a curved road, a vehicle needs to slow down before negotiating the curved road in order to ensure driving safety. However, driver usually