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Hardware-in-the-loop testbed for evaluating connected vehicle applications

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ABSTRACT

Connected vehicle environment provides the groundwork of future road transportation. Researches in this area are gaining a lot of attention to improve not only traffic mobility and safety, but also vehicles' fuel consumption and emissions. Energy optimization methods that combine traffic information are proposed, but actual testing in the field proves to be rather challenging largely due to safety and technical issues. In light of this, a Hardware-in-the-Loop-System (HiLS) testbed to evaluate the performance of connected vehicle applications is proposed. A laboratory powertrain research platform, which consists of a real engine, an engine-loading device (hydrostatic dynamometer) and a virtual powertrain model to represent a vehicle, is connected remotely to a microscopic traffic simulator (VISSIM). Vehicle dynamics and road conditions of a target vehicle in the VISSIM simulation are transmitted to the powertrain research platform through the internet, where the power demand can then be calculated. The engine then operates through an engine optimization procedure to minimize fuel consumption, while the dynamometer tracks the desired engine load based on the target vehicle information. Test results show fast data transfer at every 200 ms and good tracking of the optimized engine operating points and the desired vehicle speed. Actual fuel and emissions measurements, which otherwise could not be calculated precisely by fuel and emission maps in simulations, are achieved by the testbed. In addition, VISSIM simulation can be implemented remotely while connected to the powertrain research platform through the internet, allowing easy access to the laboratory setup.

1. Introduction

Technologies associated with Inter-Vehicle Communications (IVC) and Vehicle-Infrastructure Integration (VII) have not only gained traction in research communities, but also policy makers with the Department of Transportation's proposal for installing communication devices in new vehicles in the near future. Traffic information sharing between vehicles, also known as connected vehicle, is therefore seen as the future of road transportation to improve traffic mobility and safety. Connected vehicle technology also allows better optimization of a vehicle's fuel economy and emissions by utilizing traffic information such as the traffic light Signal-Phase-and-Timing (SPaT) and surrounding vehicles speed information.

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Researches in utilizing connected vehicle technology to optimize fuel use and emissions are mostly done in simulations, while actual testing on real vehicles is limited due to safety, cost and technical challenges. Consequently, the simulation results may not represent the actual fuel and emissions benefits precisely. A Hardware-in-the-Loop-System (HiLS) is therefore proposed to offer the flexibility and accuracy of evaluating the performance of connected vehicle applications. The HiLS is comprised of a microscopic traffic simulator (VISSIM) and a laboratory powertrain research platform. VISSIM is used to simulate a traffic network while the powertrain research platform, which consists of a real engine, an engine-loading device (hydrostatic dynamometer) and a virtual powertrain model is used to represent a single vehicle. A connected vehicle application such as the Cooperative Adaptive Cruise Control (CACC) can be simulated in VISSIM, where a target vehicle is selected to be represented by the powertrain research platform. This is done by sending the simulated target vehicle speed and road condition information from VISSIM to the powertrain research platform in real-time during simulation. This information is used to calculate the vehicle load demand, which is realized by the engine and powertrain. Fuel consumption and emissions from the engine are measured by precise laboratory equipment.

Currently the performance of a vehicle's fuel economy and emissions in traffic is measured through either simulation or by instrumenting the vehicle. First, a simulation-based approach replaces the engine with steady-state fuel-use and emission maps and therefore may not be accurate compared to actual measurements as proposed in the HiLS. Secondly, instrumenting vehicles is time consuming and expensive since it requires major modifications of the vehicles. In addition, equipping large precision measurement devices on small passenger vehicles is challenging for testing purposes.

The HiLS utilizes a real engine for direct fuel and emission measurements. Furthermore, different vehicles can be tested quickly and flexibly by changing the engine and the load settings on the dynamometer. The HiLS can also accommodate large precision measurement devices since it is built in a laboratory setting. Testing connected vehicle applications in a simulated but realistic traffic is more economical without having to instrument multiple vehicles. It is also safer and bypasses the legalities that would otherwise hamper the evaluation of connected vehicle applications in real traffic.

2. Literature review and background

Technologies utilizing IVC and VII (Ma et al., 2009; Paikari et al., 2014) have gained attentions to improve traffic safety and mobility. The Dedicated-Short-Range-Communication (DSRC) used for traffic communication has been proven to be reliable (Bai and Krishnan, 2006; Chen et al., 2007; Kenney, 2011) and field works have been done to evaluate the scalability, security and interoperability of DSRC communications in a real world setting (Dopart, 2014). Rigorous tests were also done to investigate DSRC communication reliability under different cooperative active safety applications (Sepulcre et al., 2013). Reliable IVC and VII make it possible to utilize the abundance of traffic information for numerous connected vehicle applications, including for vehicle fuel consumption and emissions improvements by merging traffic information with powertrain optimization.

Several studies have been conducted to incorporate traffic information into vehicle powertrain optimization (He et al., 2012a, 2012b, 2012c; Manzie et al., 2007). He et al. (2012a) investigated fuel efficiency and emission improvements by implementing VII on a series hybrid-electrical-vehicle (HEV) and Plug-in HEV (PHEV), which is then interpolated to a network-level cost-benefit analysis with a 15-year projection to determine the minimum penetration rate. Some analyses have also been done on the effects of prediction lengths, total mileages, driving cycles and prediction errors, using standard driving cycles, to the fuel consumption of a power-split PHEV (He et al., 2012b). He et al. (2012c) and Manzie et al. (2007) utilized predicted driving cycles and simple kinematic equations to recalculate a less aggressive driving scenario for fuel economy. Future road-grade information has also been used with HEV energy management strategy to save fuel (Zhang et al., 2010). Ranjan and Li (2011) used vehicle load data with a constant-acceleration probabilistic model in road segments, derived from historical traffic data to estimate the total electrical energy use for a specific trip in a pure electrical vehicle. Optimization methods such as Dynamic Programming (Zhang et al., 2010), Stochastic Dynamic Programming (Liu and Peng, 2008), Model Predictive Control or MPC (Borhan et al., 2009) and Equivalent Consumption Minimization Strategy (Zhang et al., 2010; Serrao et al., 2009) were used to incorporate traffic information for fuel and emissions benefits. Mohd Zulkefli et al. (2014) employed the Pontryagin's Minimum Principle (PMP) to implement a real-time HEV powertrain optimization using traffic prediction for fuel benefits. An integrated approach that optimizes vehicle acceleration and HEV powertrain operation simultaneously on a rolling terrain for fuel efficiency using PMP was proposed by Hu et al. (2016). Furthermore, connected vehicle applications, such as the Cooperative Adaptive Cruise Control (CACC), are also explored in terms of fuel savings. Li et al. (2009) used a multi-objective CACC that penalizes high vehicle accelerations for fuel economy utilizing MPC, while Stanger and del Re (2013) utilized a CACC that minimizes fuel based on the Brake Specific Fuel Consumption map with a constant-time headway policy for platooning. Despite numerous efforts to utilize traffic information to optimize fuel and emissions of vehicles in different traffic settings, most results rely on simulation approach which can be inaccurate. This is mainly attributed to the difficulties of conducting real field tests for emerging connected vehicle applications.

Current methods to measure the performance of a vehicle's fuel economy and emissions in traffic are done by either simulation, utilizing fuel consumption and emissions maps or by instrumenting the vehicle, but there are drawbacks of both approaches. A simulation-based approach usually employs steady-state fuel-use and emission maps as a function of the engine torque and speed, which are inaccurate compared to actual measurements especially during engine transients

(Filipi et al., 2006; Hagena et al., 2006). Furthermore, sophisticated CFD model and chemical kinetics are required to model emissions such as NO_X and soot accurately (Patterson et al., 1994; Hong et al., 2002). Averaged emissions rates corresponding to vehicle power demand levels are used in the U.S. Environmental Protection Agency's software package, MOVES, to estimate vehicles emissions, but comparisons with actual measurements shows high variability (Liu and Frey, 2015). Zhao et al. (2015) utilized a driving simulator with human drivers to investigate the benefits of eco-driving, where the fuel use and emissions are estimated from MOVES. Similarly, Hou et al. (2014) estimated the energy consumption and emissions from MOVES in an integrated traffic and driving simulators. He et al. (2015) used high-resolution event data such as traffic light status and vehicle queues collected from real roads to optimize the speed trajectory of a virtual vehicle for fuel benefit, which is estimated from the vehicle power demand. The difficulty of conducting real field tests for connected vehicle applications prompted the use of simulation approach. Moreover, different components of the complex traffic environment need to be simulated accurately to provide realistic and meaningful results.

In order to integrate different components of a traffic environment, integrated simulators and HiLS approaches are used. Hou et al. (2014) integrated PARAMICS traffic simulator with a driving simulator in real-time for connected vehicle and Vehicle Ad-hoc Network (VANET) studies. Bhavsar et al. (2014) implemented traffic routing strategy based on energy and travel time in MATLAB-Simulink, which is coupled with VISSIM traffic simulator for simulating traffic dynamics. In order to simulate a realistic car-to-car communication, the NS-2 network simulator is integrated and synchronized with CARISMA traffic simulator through TCP connection (Schroth et al., 2005). Similar platform was developed that synchronized PARAMICS traffic simulator with NS-2 network simulator to implement travel-time prediction methods using artificial intelligence (Ma et al., 2012). In some cases, a component of traffic environment cannot be modeled accurately by simulation, prompting the use of a HiLS that integrate actual hardware with simulation packages. For example, in order to evaluate the actual performance of implementing complex traffic signal control algorithm on actual signal controller, Bullock and Catarella (1998) utilizes CORSIM traffic simulator and sends simulated detector information to a physical signal controller. Similar HiLS structure is developed that integrate VISSIM traffic simulation with Econolite ASC/2-2000 signal controller (Ma, 2008). The main objective of the proposed HiLS is to accurately evaluate fuel and emissions performance of connected vehicle applications. Powertrain dynamics can be modeled accurately through simulation such as the ones developed by the NREL (Wipke et al., 1999; Senger et al., 1998), while calibration of traffic simulation software can provide reasonable estimate of actual traffic dynamics (Manjunatha et al., 2013). However, as discussed, fuel consumption and emissions models are very complex and cannot be accurately simulated. Therefore, a real engine has to be utilized to provide accurate fuel and emissions measurements in real-time.

For accurate measurements, Mensing et al. (2014) utilized a real engine with an engine loading device to measure the fuel and emissions performances of an eco-driving approach with predefined standard driving cycles which however lack realistic background traffic dynamics. In order to incorporate real traffic dynamics while measuring actual fuel consumption and emissions, road vehicles are instrumented. However, instrumenting a vehicle is difficult and time consuming (Duoba et al., 2000; Liu and Frey, 2015). With a HiLS, different vehicles can be tested quickly and flexibly by changing the engine and the load settings on the hydrostatic dynamometer. Equipping large precision measurement devices on large vehicles such as buses (Hu et al., 2009) or trucks (Takada et al., 2004; Norbeck et al., 2001) may be feasible, but would be challenging for smaller passenger vehicles. Smaller portable measurement devices can be used, but are less accurate, especially during engine transients and require calibrations for different driving cycles (Daham et al., 2005; Li et al., 2006). Finally, testing connected vehicle technologies in a simulated but realistic traffic is more economical without having to instrument multiple vehicles and safer than in real traffic where uncertainties are present (Hall and Tsao, 1997; Thorpe et al., 1998).

3. Objective and scope

First, the main objective of the HiLS is to merge a powertrain research platform with a traffic simulator, VISSIM. Using the powertrain research platform, a real engine can be loaded through an engine-loading device while fuel and emissions are measured in real time. VISSIM on the other hand provides the dynamics of a selected vehicle and road environment to calculate the engine load, while simultaneously simulating the background traffic dynamics. Secondly, remote communication between the powertrain research platform and VISSIM has to occur in real-time. Flexible operation of VISSIM in a remote location will allow researchers from different locations to conduct traffic simulations and collect real fuel and emission measurements quickly without being present at the powertrain research platform facility. Real-time communication is needed to ensure accurate tracking of the vehicle speed. Utilizing a small enough time-step, tracking error is minimized in case of communication delay. Finally, the testbed must be capable of tracking various vehicle speed profiles under different traffic scenarios accurately through the real engine and virtual powertrain to ensure various connected vehicle applications, such as the CACC, can be tested.

4. Methodology

The development of the HiLS involves the merging of different components. First the architecture of the HiLS is discussed. Then, the components of the HiLS are explained. Finally the integration of HiLS components through the HiLS Middleware is thoroughly explained.

4.1. HiLS architecture

The HiLS architecture is shown in Fig. 1. In the diagram, the powertrain research platform is located remotely from a computer running VISSIM simulation. VISSIM simulation executions and data transfer are handled by VISSIM-COM, which is a separate program coded in C# language. VISSIM-COM has three functions:

1. Controls the execution timing of VISSIM simulation at fixed time-step intervals to ensure real-time execution.
2. Extracts traffic data from VISSIM simulation at every time-step.
3. Sends traffic data from remote computer to powertrain research platform through internet network at every time-step.

Details of execution timing, data extraction and data sending for VISSIM-COM will be explained in the HiLS Middleware section. On the powertrain research platform side, traffic data is received and handled by the Powertrain-COM, which is also coded in C#. The Powertrain-COM has two functions:

1. Receives traffic data from VISSIM-COM through the internet network.
2. Sends traffic data to the hardware controller in MATLAB-Simulink at fixed time-step intervals.

The traffic data received is used to calculate the vehicle load where a powertrain optimization method is then used to optimize the engine torque and speed. The desired optimal engine operating point is then tracked by the hardware controllers, while fuel consumption and emissions from the engine are measured. Actual engine operating point readings are then used to calculate the realized vehicle speed in the virtual powertrain dynamics. If needed, the realized vehicle speed can also be sent back to VISSIM through the middleware to reflect (1) the powertrain dynamics and constraints, such as engine and gear shift delay and battery state-of-charge limits, and (2) the realized vehicle power from powertrain optimization. Details of the hardware controllers will be further discussed in the HiLS Components section.

In the powertrain research platform, the hardware operates continuously, while Powertrain-COM feeds updated traffic data at fixed time-step intervals to the hardware controller. This is unlike VISSIM-COM, which controls the executions of VISSIM simulation at every time-step. The two COM-softwares also ensure VISSIM and the powertrain research platform operations are synchronous. Details of the powertrain research platform and VISISM are discussed in the HiLS Components section. The HiLS Middleware, consisting of the Powertrain-COM, VISSIM-COM and network communication between them, is discussed subsequently.

4.2. HiLS components

The main components of the HiLS are the Powertrain Research Platform, which represents the target vehicle being tested, and VISSIM traffic simulator, which provides the target vehicle dynamics and road conditions.

4.2.1. Powertrain research platform

The proposed HiLS will utilize an existing powertrain research platform that was developed in the University of Minnesota (Wang and Sun, 2010; Wang et al., 2011a, 2011b; Wang and Sun, 2015) as shown in Fig. 2. The platform was developed to expedite the investigation of vehicle powertrain architectures and control strategies to engine's fuel consumption and emissions. The platform consists of a real engine and a hydraulically actuated engine loading device (dynamometer),

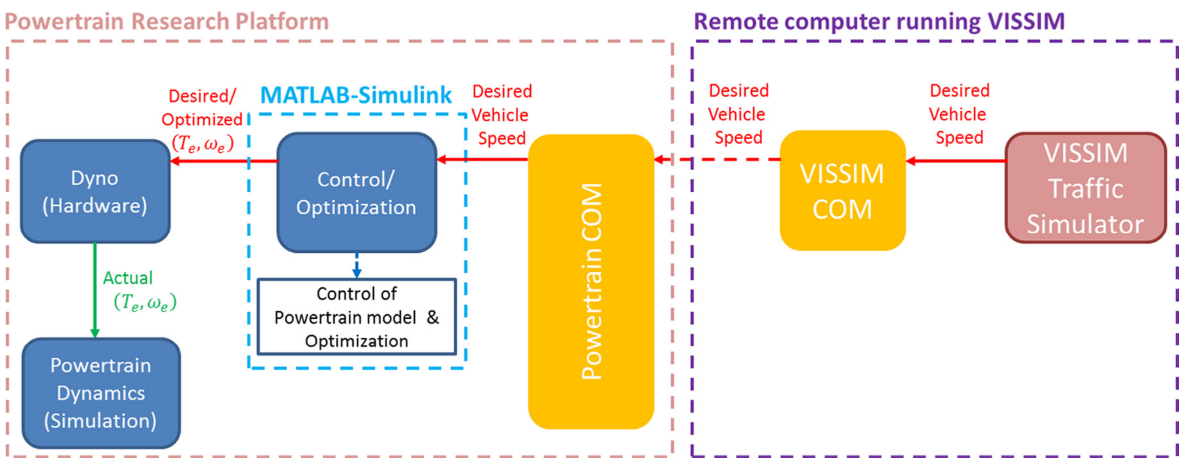

Fig. 1. HiLS architecture.

Fig. 2. Powertrain research platform.

while the vehicle powertrain dynamics and controls are captured virtually through simulation. A real engine is used because the combustion and emission behavior of an engine is too complex to be modeled accurately (Patterson et al., 1994; Hong et al., 2002) for real-time application, while the dynamics of a powertrain can be captured accurately with well-developed models.

The control and simulation is defined by a three-level closed-loop architecture (Wang and Sun, 2010, 2015; Wang et al., 2011a, 2011b). In the high-level controller, given a power demanded from the vehicle, the user-defined energy management system (EMS) will select a reference engine operating point that optimizes fuel-use and emissions. In the middle-level controller, the virtual-torque-controller will control the powertrain torques that realizes the reference engine torque from the high-level controller. Well-developed models are used to simulate the dynamic responses of the powertrain components, which include the desired engine loading torque. In the low level controller, the dynamometer is then controlled to track the desired engine loading torque from the middle-level controller. Fuel consumption and emissions from the engine can then be measured by precision measurement instruments.

Fuel consumption is measured by AVL's Fuel Measurement System Model P402 with measurement uncertainty of 0.1% and output frequency of up to 80 kHz. The emissions are measured using AVL's SESAM-FTIR, which can measure up to 25 components of exhaust gas from engine combustion including NO_X, CO, CO_2 and HCHO with a sampling rate of 1 Hz.

4.2.2. VISSIM microscopic traffic simulator

VISSIM is a commercial microscopic traffic simulator which is based on the Wiedemann's car following model (Wiedemann, 1974) and has been used extensively for various applications related to traffic evaluations. The software allows users to access traffic simulation states, such as vehicle speed, road conditions and signal phase and timing, at every simulation time-step. A simple network communication model is programmed as a dynamic-link-library (DLL) in VISSIM, by fitting experimental data from the Safety Pilot Model Deployment Program (Dopart, 2014), to simulate the BSM packet drop in V2V communication. The model provides the probability of BSM data transmission success based on the distance between two communicating vehicles. Data transmission success or failure between every two vehicles at each time step is then determined as a random occurrence based on the probability.

4.3. HiLS middleware

The HiLS middleware consists of the Powertrain-COM and VISSIM-COM. First, local communications which define the interactions of VISSIM-COM with VISSIM simulation and Powertrain-COM with the powertrain research platform controller are discussed. Then, internet network communication between Powertrain-COM and VISSIM-COM is explained. Finally, data synchronization from VISSIM simulation data extraction to data transfer to the hardware controller is discussed.

4.3.1. Local communications

Both VISSIM-COM and Powertrain-COM utilize the Component-Object-Model (COM) interface which is a standard for inter-software communication (Box, 1998). Software packages that are built with COM capability allow predefined objects in the software packages to be readable and writeable by an external program, which is usually written in a programming language.

VISSIM is a COM-capable software. Traffic data, such as the target vehicle speed and road angle, are predefined as COM objects in VISSIM and therefore accessible from an external program (VISSIM-COM) after each simulation time-step. In addition, the execution of VISSIM simulation-run at every time-step can be triggered by VISSIM-COM. Therefore, when executed, VISSIM-COM performs the following:

1. Initialize VISSIM software and load the simulation files.
2. Perform a single time-step simulation run.
3. Extract the desired traffic data and send it to Powertrain-COM over internet network.

4. Wait until the end of the real-clock time-step.
5. Repeat Step 2 to 4 until the end of simulation.

For faster extraction of large traffic data (Step 3), instead of accessing COM objects, a DLL that runs internally in VISSIM sends the desired traffic data to a User-Datagram-Protocol (UDP) virtual network port on the local computer that can be accessed by VISSIM-COM. For connected and autonomous vehicle applications, VISSIM-COM can transfer the large traffic data to an external connected vehicle controller to calculate the desired speeds for selected vehicles. The desired vehicles speeds are then sent back to VISSIM and the Powertrain-COM through VISSIM-COM.

Details of the Powertrain-COM are discussed as follows. COM is also enabled in MATLAB through the MATLAB COM Automation Server. Unlike VISSIM whose COM objects are predefined, MATLAB COM Automation Server allows access to parameters in MATLAB-Simulink blocks and user-defined MATLAB workspace variables. With this feature, the Powertrain-COM performs the following:

1. Requests traffic data from VISSIM-COM over the network.
2. When traffic data is received, it updates the parameters in the high-level powertrain controller in MATLAB-Simulink.
3. Maintains the value of traffic data until current real-clock time-step is over while keep requesting for updated traffic data.
4. Use updated traffic data received in Step 3 in the next time-step and repeat Step 2 to 4 until the end of VISSIM simulation.
5. Throttles down the real engine once VISSIM-COM sends signal to indicate the end of simulation.

Note that before the Powertrain-COM is initiated, the hardware is already running at a predefined constant vehicle load. This load will then change when updated traffic data is received.

4.3.2. Network communication

Transmission-Control-Protocol (TCP) is used as the network communication transport protocol because of the reliability of data transfer and ordered data delivery. In TCP, buffer memories are allocated on VISSIM-COM side for data sending and on Powertrain-COM side for data retrieval. These buffers ensure that data is not lost during the transfer. TCP also ensures the order of data is preserved on the receiving side, which is important in the HiLS application to distinguish the traffic data contents. User-Datagram-Protocol (UDP) transport protocol is faster than TCP, but is not used due to unreliable data transfer and disordered data. Reliable and ordered data delivery is important because data loss will affect the accuracy of the tests, while elements of the received traffic data have to be distinguished for calculation purposes. Although TCP is relatively slower than UDP, it is fast enough for the HiLS application.

At start-up, Powertrain-COM is designed to continuously send requests for a connection with VISSIM-COM. In order to establish a connection, VISSIM-COM opens a port in the socket of the remote computer running VISSIM to accept connection request from the Powertrain-COM. The socket address is defined by the internet protocol (IP) address of the remote computer and the port number. Therefore, socket connection is established as soon as VISSIM-COM opens the port.

Utilizing TCP, VISSIM-COM and Powertrain-COM sends and retrieves data from their respective buffer memories. However, since network connection is established between the two buffers, the COM-softwares will not be informed if interruption occurs in the internet network. It is therefore a common practice in TCP applications to include a keep-alive data to check the status of the internet connection between the buffers. Utilizing the keep-alive data, the Powertrain-COM will throttle down the engine if it detects a severe network interruption to ensure the engine is at a suitable operating point before shutting down for safety purposes and to avoid hardware damage.

When VISSIM simulation is completed, VISSIM-COM will close the network socket port and notify Powertrain-COM to throttle down the engine for hardware shutdown.

4.3.3. Data synchronization

The process of communication at every time-step is depicted in Fig. 3. Fixed time-steps are maintained on both VISSIM and the powertrain research platform by VISSIM-COM and Powertrain-COM respectively to ensure data synchronicity. Data transfer has to be maintained at every time-step to ensure a real-time execution. At the same time, the smallest possible time-step needs to be maintained by both VISSIM-COM and Powertrain-COM to avoid data aliasing for test accuracy. Note from Fig. 3, certain tasks need to be executed by both COM-softwares. The time durations to execute these tasks need to be considered when choosing the appropriate time-step to be maintained by both COM-softwares. For VISSIM-COM, the tasks to be completed in a single time-step are running a single VISSIM simulation time-step and extracting traffic data from VISSIM, which takes about 5 ms and 7 ms respectively. Note however the times taken to perform the tasks are dependent on the performance of the computer running VISSIM and VISSIM-COM, in our case an Intel® i5 with 2.5 GHz processor and 8 GB of RAM. Traffic data is then sent to the Powertrain-COM over internet network. The transfer time takes less than 0.1 ms using the University of Minnesota network at a distance of 2 miles between the COM-softwares. Once the traffic data is received, Powertrain-COM sends the data to the high-level controller in MATLAB-Simulink, which takes about 40 ms. This latency is due to priority conflict with the executions of data plotting in the Graphical User Interface (GUI) used by the powertrain research platform controller. The data is then used to calculate the vehicle load for engine operating point optimization.

From the above, the total time to complete all tasks does not exceed 100 ms. A time-step of 100 ms may be used, but a 200 ms time-step is instead chosen to take into consideration of other possible delays in future HiLS applications. For

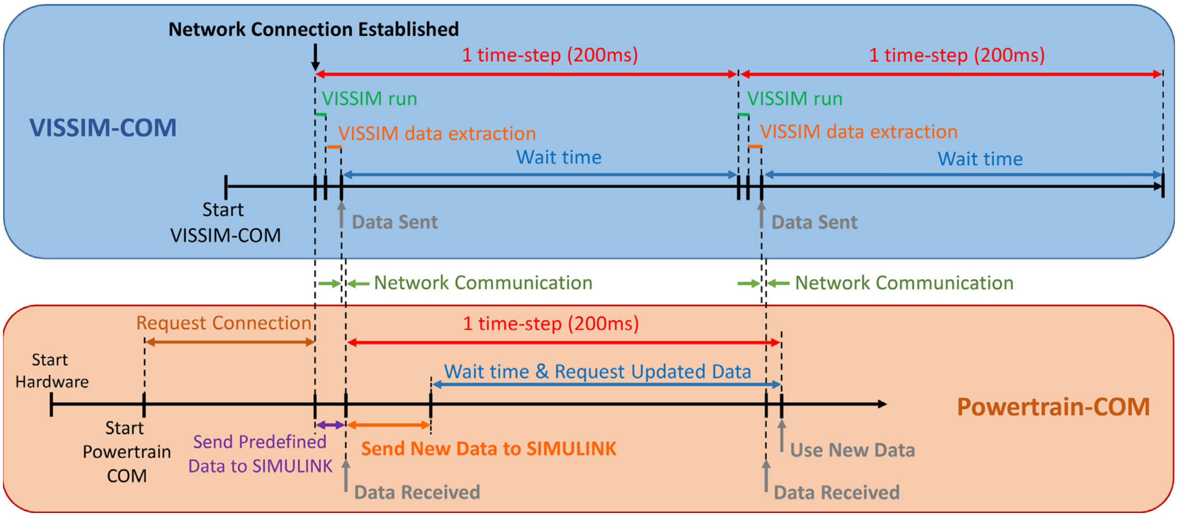

Fig. 3. HiLS data synchronization.

example, a more complicated engine optimization method may increase the processing time on the powertrain research platform side, while increased traffic data extraction will delay the VISSIM-COM side. Therefore, a wait-time is implemented in both Powertrain-COM and VISSIM-COM to maintain a time-step of 200 ms. Note however that the processing times can also be shortened with faster computers. Fig. 3 shows the HiLS data synchronization between the two COM-softwares.

5. Test results and discussions

Tests were conducted to show the capability of the HiLS. First the experimental setup is explained. Then the test results are presented and discussed. Finally, the conclusion of current works and future directions of the testbed are presented.

5.1. Test setup

The tests are first performed with a simple traffic network. Then a more complex traffic network with higher vehicle speed dynamics is used to further demonstrate the capabilities of the testbed. The computer running VISSIM simulation is located 2 miles away from the engine lab where the powertrain research platform is located. Details of the traffic networks are as follows.

5.1.1. Simple traffic network

A simple unidirectional 1700 m traffic network with zero grade angle was built in VISSIM with 7 fixed-timing traffic-light intersections at every 200 m from 300 m to 1500 m. VISSIM simulations are conducted beforehand to identify the target vehicle ID with the desired number of stops (no-stop, 1-stop, 2-stops and 3-stops) as shown in Fig. 4.

5.1.2. Complex traffic network

A complex traffic scenario was used from VISSIM's example demo BRT-priority-Texas. The main arterial network is based on a 3.5 km stretch on Medical Drive between the intersections of Babcock Road and Fredericksburg Road in San Antonio, Texas as shown in Fig. 5. The complexity of the network include (1) multiple vehicle types such as cars, busses and trucks (2) multiple lanes in each direction with vehicles lane-changing and bus stops (3) varying speed limits for roads and lanes (4) seven signalized intersections and six non-signalized intersections (5) reduced vehicle speeds, right-of-ways and pedestrian crossings at intersections (6) Ring-and-Barrier Controllers (RBC) and right-turn on red at signalized intersections (7) stop signs at non-signalized intersections.

The traffic simulation features are detailed enough that calibration works can be done to fit the parameters with real-world data. However, for the purpose of testing the testbed, the default parameters in the VISSIM demo are used. Two vehicles with 2-stops and 3-stops traversing the same path in Fig. 5 are selected as test cases. Fig. 6 shows the vehicle speed trajectories.

5.1.3. Powertrain research platform setup

On the powertrain research platform side, a Rule-Based optimization (Besnier and Rousseau, 2002) is used in the high-level controller to optimize the engine operating points based on the vehicle load. The test engine is a 115 horsepower,

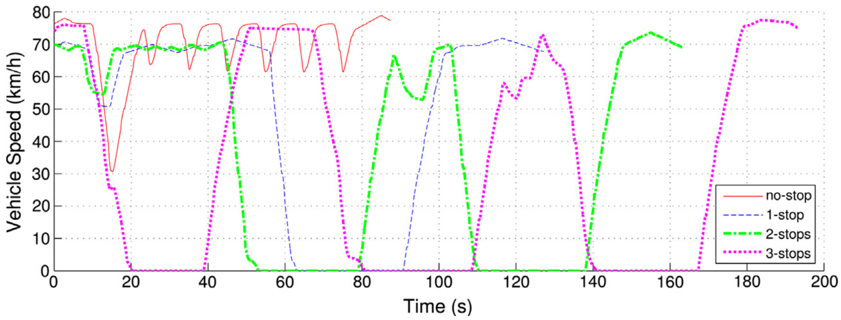

Fig. 4. Vehicle speeds for simple traffic network.

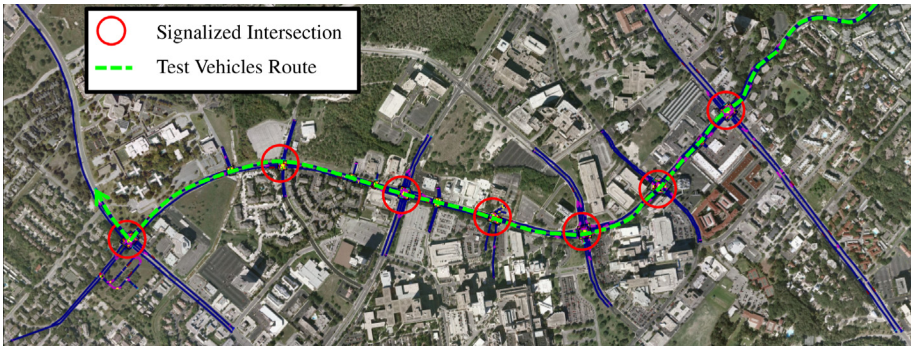

Fig. 5. BRT-priority-Texas traffic demo from VISSIM.

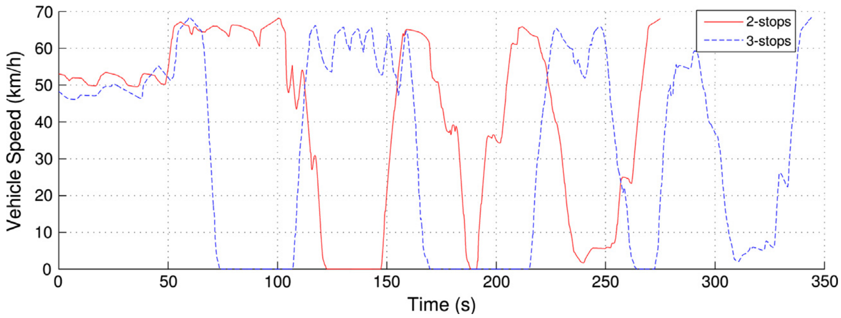

Fig. 6. Vehicle speeds for complex traffic network.

turbocharged diesel engine, which is a representative of a small, lightweight diesel vehicle. The virtual powertrain is a hybrid electrical power-split with a planetary gear set, two electrical motors/generators and a battery as the main components. Details of the virtual powertrain model, control strategies and hardware setup are documented in the references (Wang and Sun, 2010, 2015; Wang et al., 2011b).

5.2. Simple traffic network test results

5.2.1. Vehicle dynamics and measurements of fuel consumption and emissions

Fig. 7 shows the reference vehicle speed that is received and tracked by the powertrain research platform, the tracked engine operating points, the dynamics of the virtual hybrid powertrain and the measured fuel consumption for the 3-stops case. Note the torques and speeds of the generator and motor are generated from the virtual hybrid powertrain model. Fig. 8 shows the measured emissions. Test results show accurate tracking of the desired vehicle speed, engine speed and engine torque with Mean Absolute Percentage Deviation (MAPD) of 0.4%, 2% and 14% respectively. The transient nature of actual engine torque is reflected in the relatively higher MAPD.

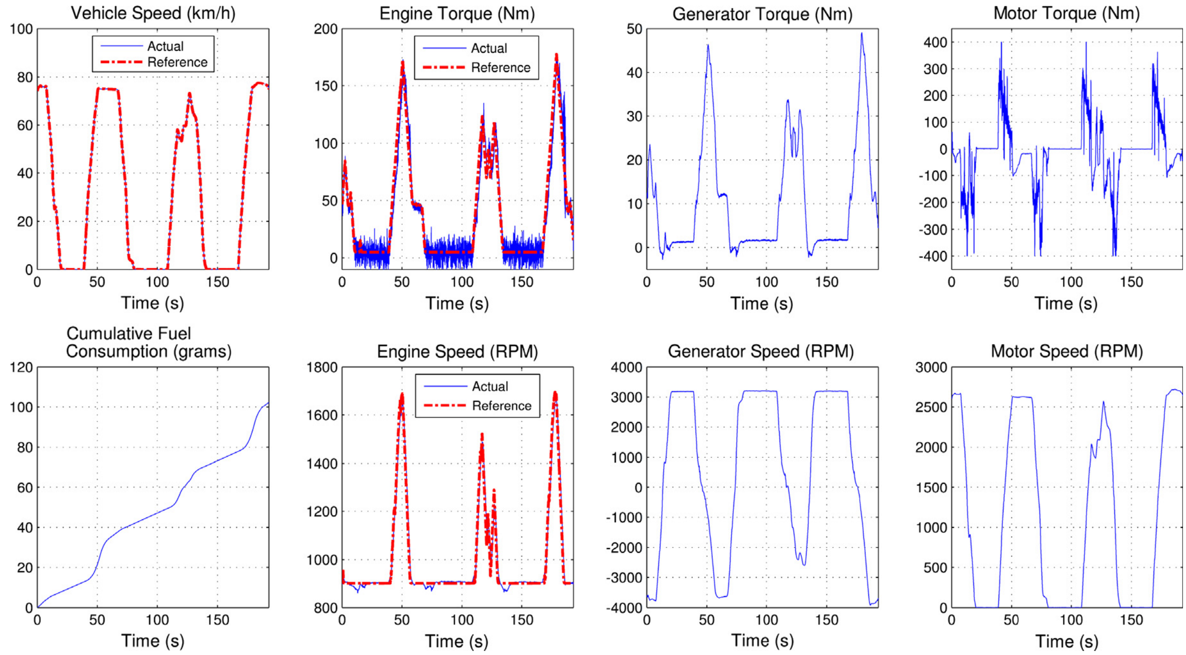

Fig. 7. Vehicle-powertrain dynamics and measured fuel (3-stops, simple traffic network).

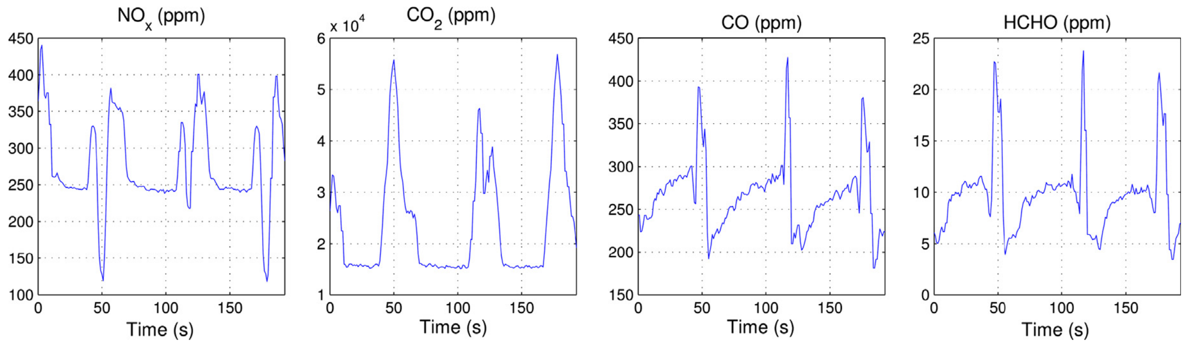

Fig. 8. Measured emissions (3-stops, simple traffic network).

5.2.2. Total fuel consumptions

Measured fuel consumptions are shown in Fig. 9. As the number of stops increases, the fuel consumption also increases due to high vehicle acceleration-deceleration and engine idling events that waste fuel and energy. The effect of driving behavior is shown between the no-stop and 1-stop cases, where the benefit of having less stops is only about 5% due to an aggressive driving behavior of the no-stop case shown in Fig. 4. The fuel use increases around 32–34% between 1-stop, 2-stops and 3-stops cases, all of which have similar level of driving aggressiveness.

5.2.3. Total mass of measured exhaust gas components

Each constituent of the exhaust gas is measured in terms of concentrations (ppm). Therefore, the formula below is used to convert the unit to mass-rate in grams per second.

$$\frac{g}{s} = \left(\frac{PPM}{10^6 \ moles \ of \ exhaust \ gas}\right) \times \left(\frac{exhaust \ mass \ rate}{exhaust \ molar \ mass}\right) \times constituent \ molar \ mass \tag{1}$$

PPM reading of a constituent is its micromole concentration per mole of the exhaust gas. The exhaust gas mole-rate (in moles per second) is found from the exhaust mass-rate (in grams per second) and the exhaust molar-mass for diesel fuel (29.4 grams per mole). The exhaust mass-rate is the summation of the measured intake-air and fuel mass-rates. Multiplying the micromole concentration of the constituent with the exhaust mole-rate gives the mole-rate of the constituent. The

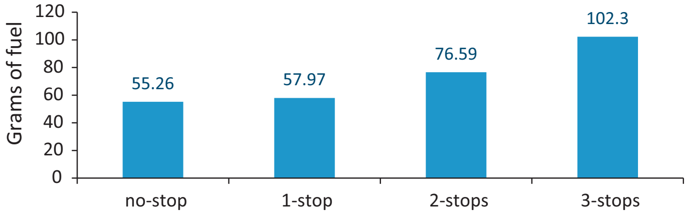

Fig. 9. Total mass of measured fuel consumed for simple traffic network.

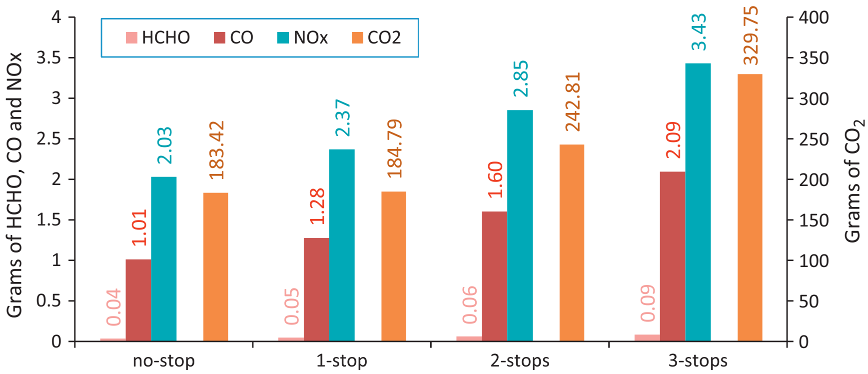

Fig. 10. Total mass of measured exhaust gas components for simple traffic network.

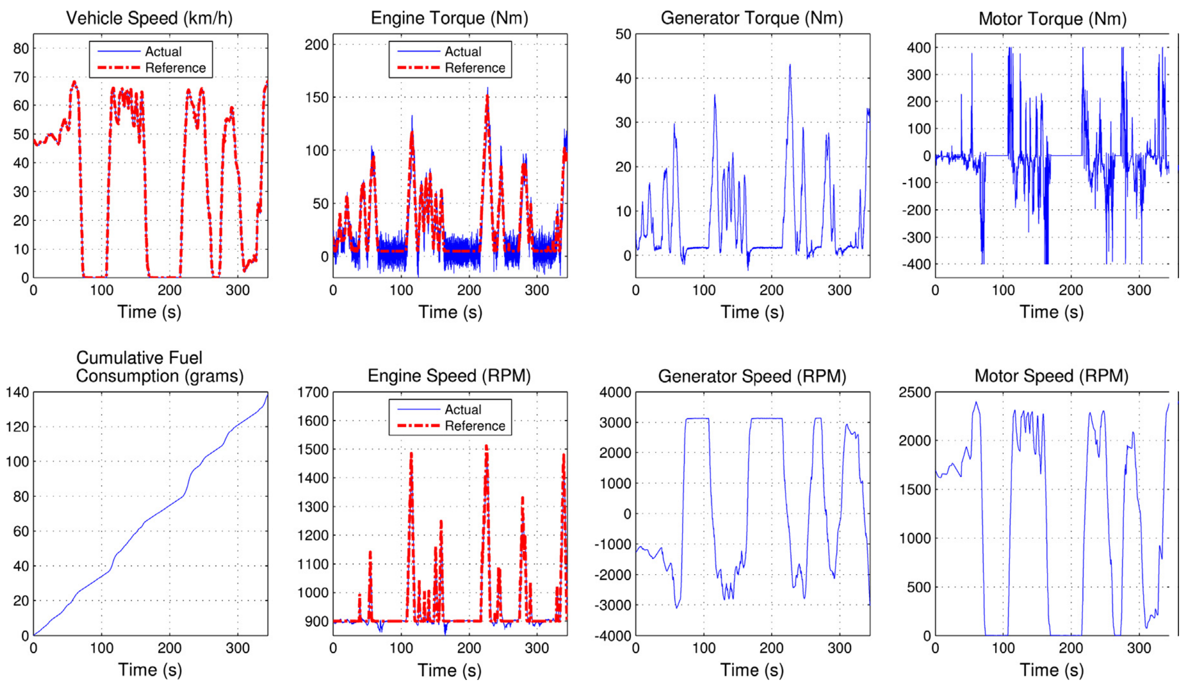

Fig. 11. Vehicle-powertrain dynamics and measured fuel (3-stops, complex traffic network).

mass-rate of the constituent is then found as the product of the mole-rate and the molar-mass of the constituent. Fig. 10 shows the total mass of the measured exhaust gas components. It can be seen that as the number of stops increases, the amount of emissions also increases.

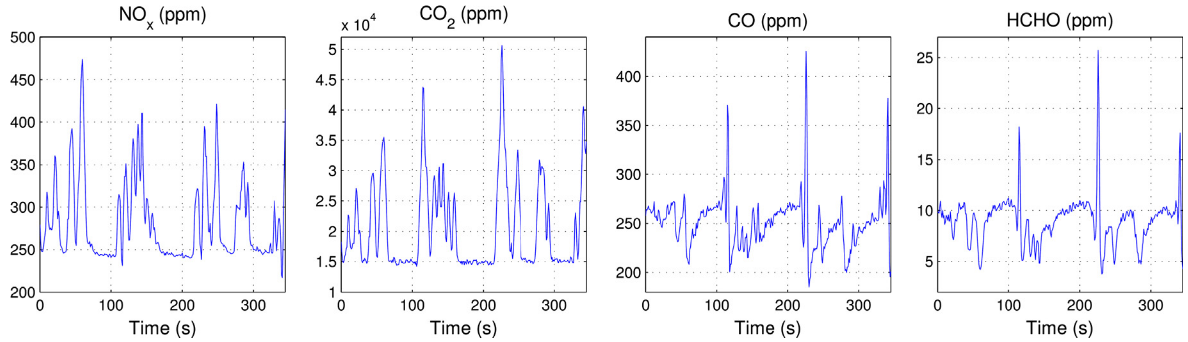

Fig. 12. Measured emissions (3-stops, complex traffic network).

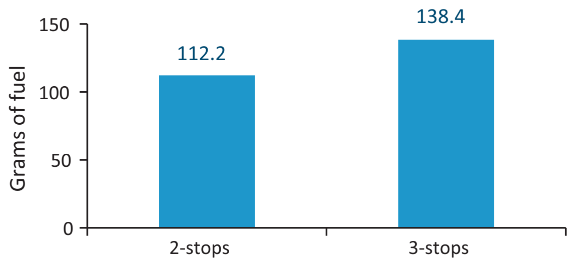

Fig. 13. Total mass of measured fuel consumed for complex traffic network.

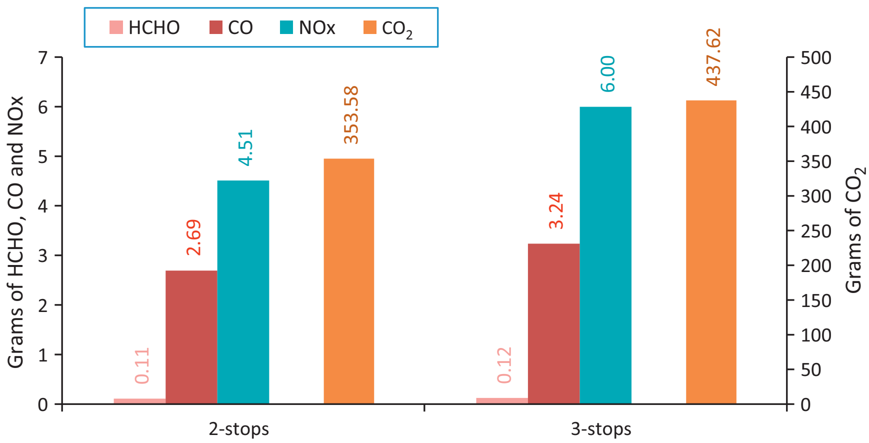

Fig. 14. Total mass of measured exhaust gas components for complex traffic network.

5.3. Complex traffic network Test results

5.3.1. Vehicle dynamics and measurements of fuel consumption and emissions

Fig. 11 shows the vehicle, engine and virtual powertrain dynamics and the measured fuel of the 3-stops case in a complex traffic network with more transient vehicle dynamics than the simple case. The desired vehicle speed, engine torque and engine speed are tracked accurately with MAPD of 0.4%, 1.5% and 16% respectively. The engine torque MAPD is slightly higher than the simple traffic due to the higher dynamics of the reference. Emissions measurements are presented in Fig. 12.

5.3.2. Total fuel consumptions

The total fuel consumptions measured for the 2-stops and 3-stops cases are shown in Fig. 13. The 3-stops case consumes 23% more fuel than the 2-stops case, which is about 10% less than the comparison between the 2-stops and 3-stops cases in the simple traffic network. This can be attributed to the more transient vehicle dynamics in the complex traffic case, where the stop and go is not the only dominant dynamics.

5.3.3. Total mass of measured exhaust gas components

Fig. 14 shows the total mass of exhaust gas components for the 2-stops and 3-stops cases in the complex traffic network. As shown, all exhaust gasses mass increase as the number of stops increases. Most notable are NO_x and CO_2 with 33% and 24% increases respectively in the 3-stops case.

5.4. Comparisons with simulation results

Simulations were performed to calculate total NO_X and CO_2 emissions using a software that estimates vehicle emissions on a policy level, but the results showed significant difference compared to measured emissions. This is attributed to the estimation errors from using averaged vehicles emissions data for a class of vehicles in the software, which is inaccurate to represent a specific vehicle. Furthermore, NO_X emission for the 2-stops complex traffic case is interpolated using a well calibrated steady-state emission map for the specific test engine. Total NO_X from simulation was found to be 4.83 g, which is 7% higher than the measured emission in Fig. 14. This shows that even with a well calibrated map, simulation results are still inaccurate due to transient engine behaviors that cannot be captured by a steady-state map.

6. Conclusion and future works

The HiLS has been tested and shown to achieve the followings:

1. Vehicle data from a remote traffic simulation have been successfully extracted and transferred in real-time to the powertrain research platform over the internet through COM interfaces and socket programming.
2. Different vehicle speed profiles are accurately tracked by the powertrain research platform to represent the target vehicle in VISSIM simulation.
3. Rule-based optimization method has been successfully employed in the powertrain research platform to optimize engine operating points in real-time, which can be extended to other optimization methods utilizing traffic data (Mohd Zulkefli et al., 2014) in the future.
4. Actual fuel consumption and emissions measurements are recorded, which can be used to evaluate various connected and autonomous vehicle applications.

In order to improve and to add more functionalities of the testbed, future works are planned as the followings:

1. Develop more comprehensive traffic simulations in VISSIM which will be evaluated and calibrated with data collected from actual roads.
2. Support the benefits assessment of several USDOT's connected vehicle applications, which include Eco-Approach, CACC, Eco-Driving and Speed Harmonization. This can be achieved by using an external connected vehicle controller linked with the HiLS testbed.
3. Improve the synchronization robustness of network communication by time-stamping transferred data and use distributed computing techniques to estimate, monitor and anticipate communication delays during HiLS operation.
4. Minimize TCP packet processing overhead by tailoring the application programming interface, network protocol and protocol implementation to the specific needs of the HiLS (Rodrigues et al., 1997).

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