Living Laboratory for Freeway Operations: Case Study for Collecting Driver Behavior Data Through Freeway Work Zones

Taylor W.P. Lochrane
Ph.D. Candidate at the University of Central Florida &
Research Civil Engineer at Federal Highway Administration
U.S. Department of Transportation
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101
202 493-3293
Taylor.Lochrane@dot.gov

Haitham Al-Deek, Ph.D., P.E.*
Professor of Engineering
University of Central Florida
Department of Civil, Environmental, and Construction Engineering
4000 Central Florida Boulevard
Orlando, FL 32816
407-823-2988
Haitham.Al-Deek@ucf.edu

Daniel J. Dailey, Ph.D.
Professor of Electircal Engineering
University of Washington
Department of Electrical Engineering
1410 NE Campus Parkway
Seattle, WA 98195
206-543-2493
dan@uw.edu

Joe Bared, Ph.D., P.E.
Team Leader, Transportation Concepts and Analysis
Federal Highway Administration
U.S. Department of Transportation
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101
202 493-3314
Joe.bared@dot.gov

*Corresponding Author

Words = 4,953
Figures & Tables = 10 x 250 = 2,500
Total = 7,453

Submitted for presentation ONLY at The 93rd Annual Meeting of the Transportation Research Board

Revised in November 2013
Originally submitted in July 2013

ABSTRACT

This paper presents the concept of a Living Laboratory (LL) and how it is applied to transportation operations research through a case study. This case study focuses on calibrating the Wiedemann car-following model parameters specific to freeway work zones. Applying the concept of a LL enables the experimental platform to be in a natural real-world environment. The design of this LL included the development of an Instrumented Research Vehicle (IRV) to capture the natural car-following response of a driver when entering and passing through a freeway work zone. The development of a Connected Mobile Traffic Sensing (CMTS) system, which included state-of-the-art ITS technologies, supports the LL environment by providing the connectivity, interoperability and data processing of the natural, real-life setting. The IRV and CMTS system are tools designed based on the research objective to support the concept of a LL which facilitates the experimental environment to capture and calibrate natural driver behavior. This case study shows the application of a LL specific to operations research providing an experimental platform for evaluating roadway's operational performance in a real-time, connected and collaborative natural environment.

INTRODUCTION

As traffic congestion continues to increase on U.S.A. highways, advances in Intelligent Transportation Systems (ITS) technology using the collection of high quality, real-time data can assist travelers and transportation management centers (TMCs) with real-time and reliable traffic information. This data is also being used off-line in the transportation industry to conduct traffic studies and to evaluate roadway conditions for both mobility and safety.

In today's connected world, technological advances in various forms of technology are offering engineers and researchers the capability to conduct experiments outside of the typically controlled laboratory environment or limited field demonstration and testing experimentations. The idea for conducting experiments in real-world environments will be referred to here as the Living Laboratory (LL). These living laboratories enable real-time research for testing and evaluation of transportation concepts that can improve both mobility and safety of our transportation system. This paper will describe a case study for setting up a LL for advancing research in the area of freeway work zones.

For transportation agencies, work zone safety and mobility are a growing challenge on U.S. highways due to the growing demand on the transportation network. One method used by engineers to evaluate designs and forecast congestion performance involves the use of modeling and simulation. Calibration and validation of the simulation models using field data is essential to ensure that models produce accurate results. The LL, described in this paper, involves building an Instrumented Research Vehicle (IRV) and the development of a Connected Mobile Traffic Sensing (CMTS) system to collect and transmit real-time roadside data. The integration of specific sensors on the IRV, in combination with CMTS roadside data, will assist in model calibration and validation of car-following parameters.

The objective of this paper is to define and describe a LL specific to transportation operations research. This paper is organized into two sections. The first section describes the emerging use of LL and applying LL to transportation research. The second section details a case study for the implementation of a LL that is designed to capture work zone driver behavior. In the latter section, the methodology and technology development for collecting driver behavior data used to establish the LL is described.

EMERGING LIVING LABORATORIES (LL)

The concept of a Living Lab (LL) surfaced in Europe around the turn of the century. The idea behind this concept was motivated by developing a research program that focused on interactions with intelligent environments. For example, the first LLs emerged in the area of new technology for future homes involving real people and their interaction with new devices. The vision of this LL would serve as a platform for collaborative research for developments and testing of new technologies *(1)*. Over the past decade the concept of a LL has evolved in Europe, being defined: (1) as an environment *(2)*, (2) as a methodology *(3)*, and (3) as a system *(4)*. These three definitions seem to be complimentary and have been combined to define a Living Lab as "a user-centric innovation milieu built on every-day practice and research, with an approach that facilitates user influence in open and distributed innovation processes engaging all relevant partners in real-life contexts, aiming to create sustainable values" *(5)*. This definition is based on LLs that have focused mainly on developing new technologies, services and applications in real-world environments to promote product creation. A user-centric innovation is where the user is part of a system rather than a user being the reason for the system. This concept evaluates the user reactions and acceptability to experiences in real-world surroundings. This paper applies the concepts of the original European Living Labs to develop a LL specific to traffic operations research in the United States.

APPLYING LIVING LABORATORIES TO TRANSPORATION RESEARCH

A Living Laboratory, specific to transportation operations, is defined here as a roadway network, corridor or regional transportation network that is instrumented with technology to promote collective leaning and collaborative research based on a user-centric innovations for evaluating operational performance. The purpose of establishing a LL is to evaluate technologies and treatments on a roadway's operational performance in a real-time, connected and collaborative environment. This is implemented using mobile and or fixed equipment placed in roadways (e.g. freeways, arterials and rural roads) to capture the real-world reaction or acceptance of conceptual strategies and treatments.

This may sound similar to the concept of a testbed but in reality they differ in experimental methods. A testbed is defined as a platform for experimentation of large deployments of scientific theories, computational tools and new technologies *(6)*. Testbeds are used for isolated testing proof-of-concept for new technologies in a controlled environment; however, a Living Laboratory focuses on a non-isolated deployment and testing in real-world environments. Living Laboratory, as used herein, is designed to be an experiment tailored to a research objective while maintaining a natural environment for the user. There are four areas driven by the research objective when designing a LL specific to transportation operations: requirements, data, location and experimentation.

1. ***Requirements:*** Outlining the data requirements (e.g. travel time, volume, occupancy, speed, gaps, etc.) will support the technology requirements (e.g., IRV, dedicated short-range communications, cellular communications, Bluetooth, video, etc.) that are essential for the architecture behind the LL. Identifying these requirements particular to the research objective will outline the experimental environment needed to take place in a real-world context.
2. ***Equipment:*** Selection of equipment to support the technology and data requirements is essential in bringing the experiment together. Integration of state-of-the-art ITS technologies with network connectivity, interoperability and data processing will provide optimal results for supporting the requirements.
3. ***Location:*** Determining a location when establishing a LL is specific to the research objective. Focusing on the requirements and equipment selected will help identify suitable locations. Working with local municipalities or State Departments of Transportation (DOT) can help with access and identification of suitable sites. Most of the road authorities have pre-installed data collection locations in the field (i.e., loop detectors, microwave sensors, etc.). These locations should be investigated to see if their locations fall within the bounds of the proposed LL. Using existing equipment may help reduce cost, however careful analysis of the reliability and data quality should be taken into consideration.
4. ***Experimentation:*** Deploying the equipment in the field for the identified LL will launch the experimental platform. This platform integrates all of the selected equipment for the

development of the LL and completes the experimental environment together, allowing for research to begin.

The above steps will help guide the design and development of the Living Laboratory. The next section will describe a case study in which a LL was built to evaluate and monitor work zone driver behavior. This case study is being executed by the Federal Highway Administration (FHWA) in Saxton Transportation Operations Lab at Turner-Fairbank Highway Research Center (TFHRC).

CASE STUDY

The motivation for this study is to look into car-following models and how they relate to work zone driver behavior. There are many different types of car-following behavior models that have been used over the past five decades. The Wiedemann psycho-physical car-following model, selected for this case study, is one of the models that take into account the driver behavior *(7)*. Wiedemann pointed out that human driving behavior is naturally distributed by the drivers having different driving abilities, perception and estimation, needs of safety, desired speeds and acceleration/declaration characteristics. There are nine different threshold values that are part of the car-following algorithm that influence capacity shown in Table 1 *(8)*.

TABLE 1 Wiedemann Model Parameter Predictions *(8)*

Variable		Default Value	Variable Name	Predicted changes to default values
Thresholds for the change in Distance *(Δx)*	CC0	4.92 ft	Standstill distance:	No significant difference is expected until **large spacing** distance is reached which would result in a significant **reduction in capacity**.
	CC1*	**0.90 sec**	**Headway Time:**	At low speeds CC0 will be the dominant factor and during high speeds CC1 will be the dominant factor in the calculation of safety distance. As CC1 **increases** there will be a substantial **reduction in capacity.**
	CC2*	**13.12 ft**	**Following Variation:**	As CC2 **increases** **capacity decreases** but when CC2 **decreases** there is a significant **increase in capacity**. The driver becomes much more aggressive when CC2 decreases which means that the driver will be speeding up and slowing down at a higher rate.
	CC3	-8.00 sec	Threshold for Entering 'Following' State:	No significant difference is expected that will impact capacity. The time it takes to slow down to reach the safety distance does not affect capacity but once the driver gets to this point, what the driver does from here is significant and is controlled by CC2.
Thresholds for the change in Velocity (*Δ*v)	**CC4***	**0.35 ft/s**	**Negative 'Following' Threshold:**	As the values for CC4 and CC5 **increase** the **capacity decreases** significantly. Default values have been questioned for being too high which results in lower capacities. As drivers become more sensitive to the preceding vehicle, i.e., **decrease** in CC5 value, the driver will then follow more closely which will **increase capacity**.
	CC5*	**0.35 ft/s**	**Positive 'Following Threshold':**	
	CC6	11.44	Speed Dependency of Oscillation:	No significant difference is expected. The following distance is the main factor in following behavior parameters that will affect capacity. As CC6 increases the speed will oscillate more but will not really affect the distance by a larger magnitude.
Acceleration Rates	CC7	0.82 ft/s^2	Oscillation Acceleration:	No significant difference is expected in capacity.
	CC8	11.48 ft/s^2	Standstill Acceleration:	No significant difference is expected in capacity
	CC9	4.92 ft/s^2	Acceleration at 50 mph:	No significant difference is expected in capacity

Note: Variables in bold with (*) are the selected variables focused on in this case study

In order to calibrate the Wiedemann model, there are several variables that need to be collected to assist in the calibration of this car-following model. According to *(9)*, the variables that are most significant in affecting capacity include: standstill distance (CC0), headway time (CC1), following variation (CC2), negative following threshold (CC4), and positive following threshold (CC5). Relative distance Δx and relative velocity Δv of two following vehicles are needed to calculate the desired safety distance (CC0 + CC1*velocity) and following variation (CC2) shown in Figure 1. Acceleration and deceleration of the IRV is needed to calculate the following thresholds (CC4 and CC5). This case study developed a methodology for collecting the data needed to calibrate psycho-physical car-following behavior while specifically focusing on the Wiedemann model.

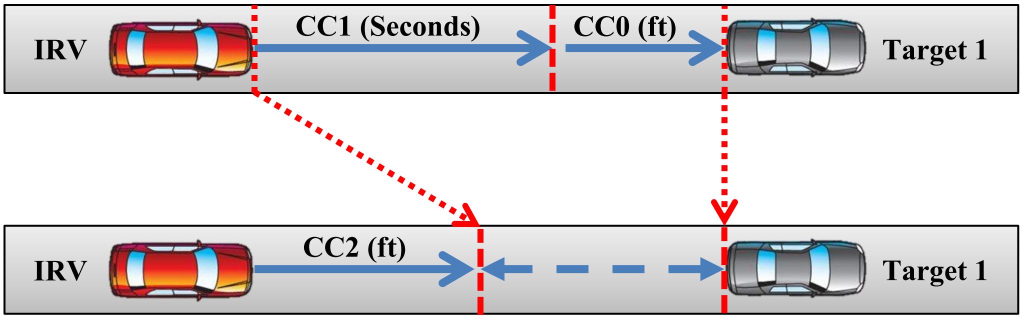

FIGURE 1: Displaying headway and following variation

TECHNOLOGY REVIEW

One of the accepted methods to collect driver behavior is observation of a driver in real-world driving conditions. With the intent of collecting data on specific driver characteristics and performance, researchers have used instrumented vehicles to capture their reactions. Some of the earlier instrumented vehicles used video imaging and data from the speedometer as methods to record driver data *(10)*. As technology has advanced over the past decade, more cutting-edge equipment has been used in this research area. One of these new technologies used by several researchers to collect vehicle gap data is LIDAR (Light Detection and Ranging) *(11),(12)*. LIDAR uses light reflectivity to image objects at rates that range from 50-100Hz to collect very high-quality data. This was originally used in the survey and mapping industries but is now being used more in the autonomous vehicle research. LIDAR provides excellent data but does have some drawbacks, for example: poor performance under rainy or snowy weather conditions; size tends to be large and hard to conceal and requires no obstruction to the view angle. Another technology that is being used by original equipment manufacturers (OEM) and researchers in the development of Adaptive Cruise Control (ACC) is radar. For example, researchers from California PATH (Program of Advanced Transit and Highways) used radar to collect data on car-following headways to see what would be acceptable for drivers using Cooperative Adaptive Cruise Control (CACC) *(13)*. Radar can provide range data relative to the location of the sensor of an object at a measurement cycle of 40 milliseconds (ms). Radar is not affected by weather and can be mounted and concealed behind a plastic bumper.

When collecting velocity, accelerations and decelerations of the vehicle, GPS receivers have been used in instrumented vehicles by researchers as a reliable and accurate source for this data *(13-15)*. GPS relies on satellites and receivers, which use a moving source of signal between them to communicate. The GPS receivers calculate velocity by determining if the Doppler shifts from the D-band carriers between four or more satellites *(16)*. This calculation of velocity at 0.2m/s per axis is a 95% guarantee accuracy of velocity *(17)*. Distance can be derived from this by taking the integral of velocity.

With the technology that is available today, the use of an instrumented vehicle to collect data for capturing and calibrating a psycho-physical car-following model to simulate the change in behavior from normal freeway driving to driving into work zones is now possible with the use of radar and GPS. Traffic data is collected using several different ITS technologies that can be deployed along a roadside. Researchers in the freeway work zone arena have identified specific variables to be considered basic information needed for analysis which include: speed, headway, volume and vehicle counts *(18),(19)*. Researchers have used a combination of different methods for collecting data such as: video cameras and loop detectors for traffic counts, laser guns for speed information and visual observations to identify work activity and current geometries of the work zones *(20-22)*.

The Living Laboratory presented includes two sources of data collection which can be used together in calibrating the Wiedemann psycho-physical car-following model for work zones: (1) scientific measurements of car-following behavior from a driver in a natural environment, and (2) relevant data (e.g., traffic conditions) of the natural, real-life environment in the LL.

METHODOLOGY

The methodology for collecting car-following data from different drivers requires the use of an Instrumented Research Vehicle (IRV). This IRV must be equipped with the capability to capture relative distance and velocity of moving targets traveling at high speeds. After reviewing all available technologies, radar was selected as the sensor to be used in the IRV. The use of 24GHz radar provided data on the target's range, azimuth angle, and radial velocity within the angle of view. Radar uses the combination of two principles: linear frequency modulated (LFM) and frequency shift keying (FSK) continuous waveforms (CW) to provide accurate multi-target identification.

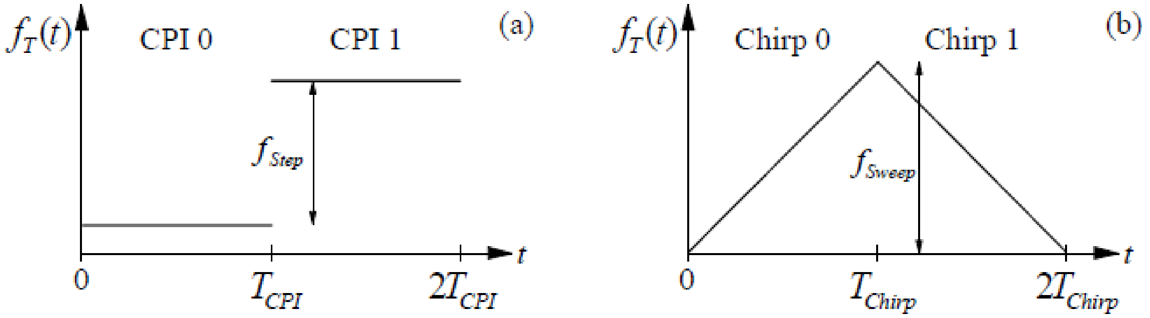

FIGURE 2: Two CW waveform principles: (a) FSK modulation, (b) Linear Frequency Modulation (LFM) *(23)*

The FSK modulation consists of two frequencies f_a and f_b and the difference between these two frequencies is known as f_{step}. These frequencies are transmitted in a coherent processing interval (CPI) T_{CPI} which has a length in milliseconds as shown in FIGURE **2:** (a). The FSK waveform is able to provide a very high-velocity resolution of an object avoiding ghost targets but does not capture the target resolution in the range direction *(24)*. The LFM waveform uses an oscillator sweep called f_{sweep} to produce a very high range and velocity resolution but is ineffective in multi-target situation considering that ghost targets may appear. These frequencies are transmitted by T_{Chirp}, which is the coherent processing interval or pulse width, and which has a length in milliseconds as shown in

FIGURE **2:** (b). Combining the FSK and LFM waveforms provides the capability of collecting unambiguous target range and velocity measurements simultaneously *(23)*. The combination of these two principles is shown in FIGURE **3**.

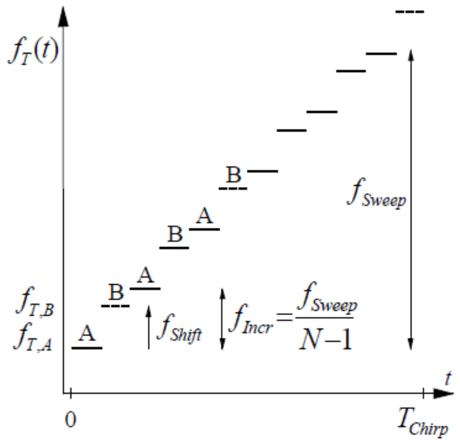

FIGURE 3: Combining the FKS and LFM waveform principle *(23)*

The IRV is equipped with two radars, forward and rear facing, to record data on the surrounding targets within the radar angle of view. The concept behind this is shown in **FIGURE 4:** , in which five vehicles, identified as targets ($V_{Taget\ \#}$), are being sensed by the radar.

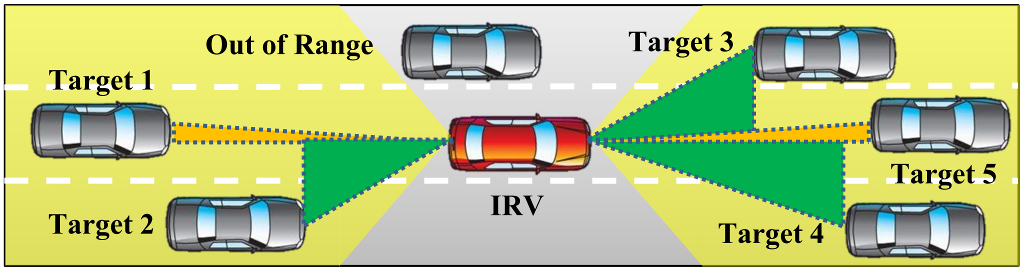

FIGURE 4: Concept for measuring the critical gap

The radar can capture speed oscillations of the IRV which are defined as unconscious acceleration and deceleration while following a vehicle. Capturing a driver's relative velocity and position over time is used for the calibration of speed oscillations based on each driver's unique behavior. The IRV is able to sense the range rate of the surrounding vehicles to identify two following conditions: (1) separation between two vehicles which is shown as a positive value, or (2) closing in / approaching between two vehicles which is shown as a negative value. Each target vehicle's relative velocity and position is derived with the data from the IRV. The equations used to calculate relative velocity of a target vehicle are listed below:

$$V_{Target\,\#} = v_{IRV} \pm \left(\frac{\Delta x_{Target\,\#}}{\Delta t}\right) \tag{1}$$

$$\Delta V_{Target\,\#} = v_{IRV} - V_{Target\,\#} \tag{2}$$

where $V_{Target\,\#}$ = relative velocity of vehicle (feet/second)
v_{IRV} = velocity of instrumented research vehicle (feet/second)
$\Delta x_{Target\,\#}$ = change in distance of vehicle (feet)
Δt = change in time (milliseconds)

DEVELOPMENT OF THE IRV

In order to collect and analyze driver-specific behavior, a vehicle is equipped with radar to capture the gaps and unconscious speed oscillations of various drivers. This is postulated to relate driver behavior in a work zone. The IRV onboard equipment includes: (1) two universal medium range radars (UMRR) to collect relative velocity and position of objects/vehicles in both front and rear, (2) a speed sensor that provides speed data through built-in algorithms using the global positioning system (GPS), (3) a video system which provides a video acquisition, and (4) a computer system for the overall data acquisition.

An early step in developing an IRV is designing a separate power system from the vehicle power system, see Figure 5. This is needed to ensure that the onboard equipment does not interfere with the vehicle computer or basic vehicle functions. Therefore, a battery isolator is installed inline from the alternator to separate the power system. The secondary battery and power system are also installed. A direct current (DC) to alternating current (AC) converter is connected to a battery backup to power all AC hardware. The battery backup would allow the transfer of power from the inverter to an AC outlet in the garage to ensure the in-vehicle equipment could be used for testing with the vehicle engine being turned off.

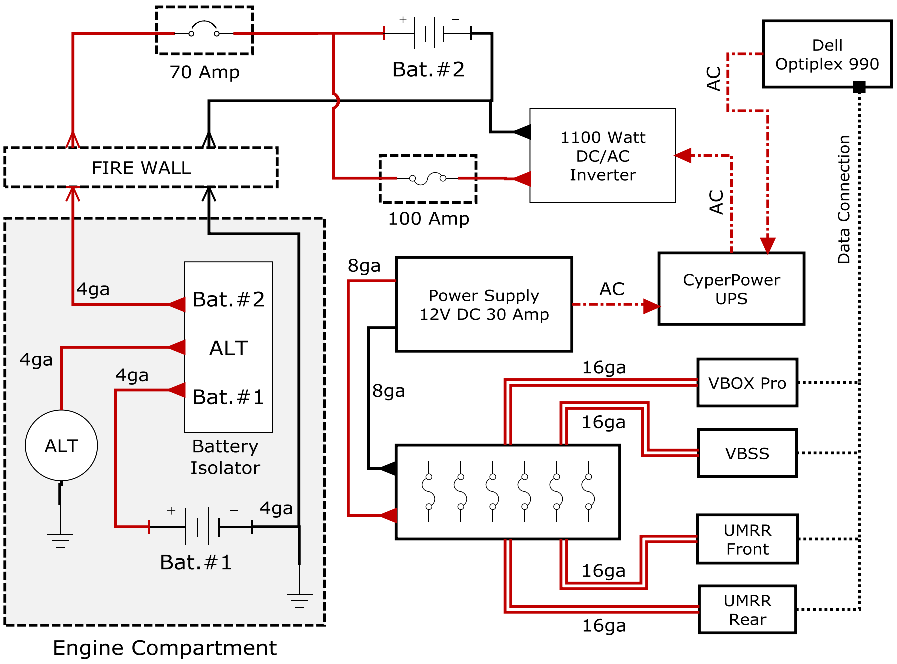

FIGURE 5: IRV Electrical diagram

The next step involves the integration of all in-vehicle equipment. This step requires different protocol connections to be included in the IRV. The main objective is to connect all of the equipment to the in-vehicle PC which houses the data acquisition software. For this network, there are four main protocols that are used in the design: RS232, Controller Area Network (CAN), Universal Serial Bus (USB), and Ethernet. The network for these protocols for in-vehicle equipment is shown in FIGURE **6:** . For the video system and speed sensor a dashed arrow is shown which indicates that they use a different protocol for setup but are connected through the CAN network as the primary protocol.

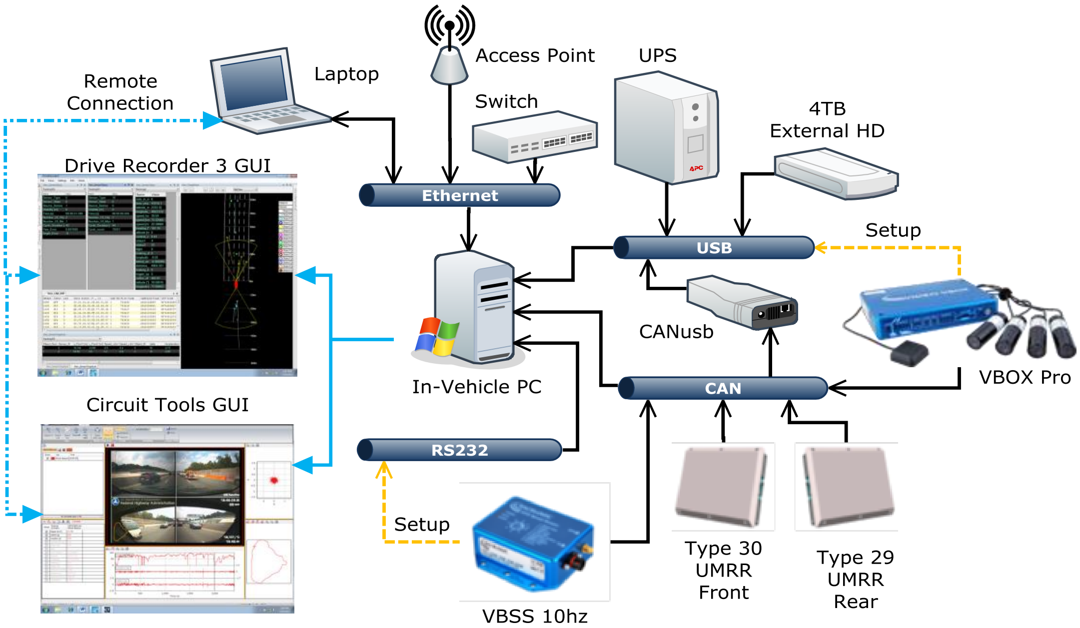

FIGURE 6: IRV In-Vehicle equipment diagram

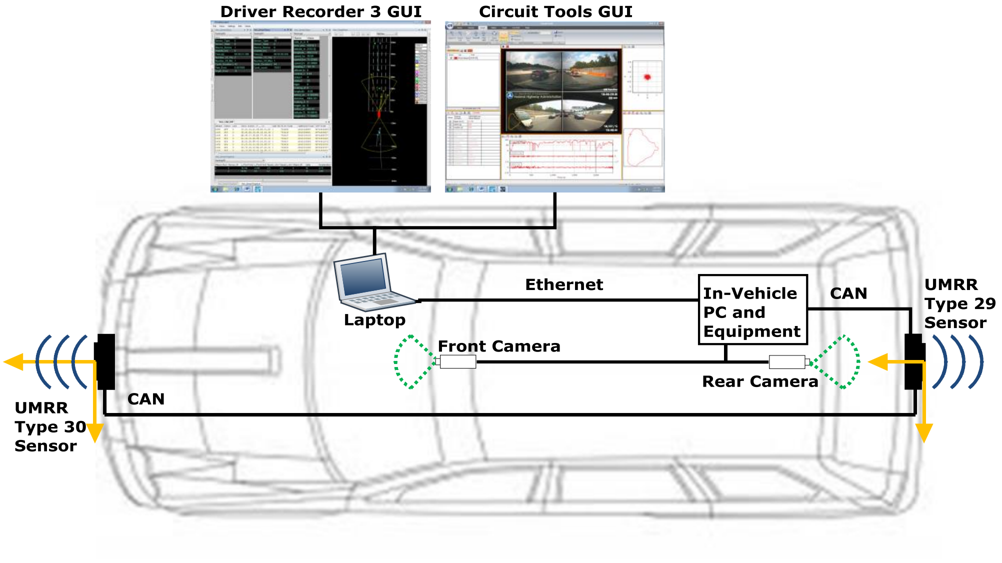

FIGURE 7: IRV video and radar sensor diagram

The IRV includes both radars and cameras which are placed in the vehicle to be inconspicuous to other drivers. As shown in Figure 7, there are two radars and two cameras that are forward looking and rearward looking. The video is to assist in the data analysis of the radar data. For example, the following vehicles may change lanes, or the following vehicle may be a truck instead of a car and may not be identified when looking at the radar data. These cameras are installed in such a way to avoid creating any obstructed views to the driver. The radar on the front of the vehicle is a Type 30 UMRR *(25)* which provides ±35 degree angle of view with a 90 meter range. The radar on the rear of the vehicle is a Type 29 UMRR *(26)* which has a ±18 degree angle of view with a 160 meter range. Since this research is focusing on car-following, it was decided to have a wider angle in the front than the rear to capture more objects in front of the vehicle. Concealing these radars on the IRV is a challenging task. The Type 30 UMRR *(25)* is installed on and extended through the front bumper. The front radar is mounted on an adjustable bracket that is used for calibration of the radar's ±8 degree angle of height. The Type 29 UMRR *(26)* is installed in the rear bumper and is concealed behind the plastic bumper of the IRV vehicle.

DATA ACQUISITION

There are two separate data acquisition systems in the vehicle: one for video and one for radar. The forward- and rear-facing video cameras located in the interior of the vehicle are logged continuously. This video data is connected to the CAN network which is linked to the speed sensor. The camera system is set up to log the GPS data through the CAN network. This allows the video data to be logged with the same "time since midnight" time reference point as the onboard software which logs the data from the radars.

The onboard software is designed to log data from the front and rear UMRRs and the speed sensor GPS data. The onboard software operates on the computer installed in the vehicle and comes with a customizable graphical user interface (GUI) which visualizes the data. The customized GUI, shown in **Error! Reference source not found.**, displays the object tracking data being logged in real-time on the left, the speed sensor data is imported and shown at the top and a visual display of all the targets are represented in real-time on the right.

View_SensorStatus

RaceLogic

Name	Value
sats_in_view	8
time_since_midnight_utc	65207.8
latitude_minutes	2324.094
longitude_minutes	4631.641
speed_knots	52.32
speed [km/h]	96.89664
speed [m/s]	26.9155
heading [°]	211.64
altitude [m]	7.87
vertical_velocity [m/s]	-0.45
status1	4
status2	33
dgps	0

View_SensorTargetList

TrackingID0

Object_Num	Sensor_ID	x_Point1 [m]	y_Point1 [m]	Speed_x [m/s]	Speed_y [m/s]	Object_Cl	state	Acceleration	rele
0	0	12.672	4	3.2	-0.2	175	18	0.51	0
1	0	21.184	0.256	0	-0.2	167	22	-0.04	1

View_SensorTargetList

TrackingID1

Object_Num	Sensor_ID	x_Point1 [m]	y_Point1 [m]	Speed_x [m/s]	Speed_y [m/s]	Object_Cl	state	Acceleration	lit
0	0	-16.832	2.976	2.1	-0.2	31	6	-6.2	2
1	0	-20.768	-0.064	0.2	0	25	6	0.12	3

View_SensorTargetList

Umrr2GID0

Object_Num	Range1 [m]	Azimuth1 [rad]	AZ_angle [°]	Amplitude	Speed_Radial [m/s]	CL_THR_Level	Object_
0	13.31	0.262448	15.04	73.92	2.94	60.8	2
1	16.71	-0.019544	-1.12	48	-15.62	39.68	1

View_SensorTargetList

Umrr2GID1

Object_Num	Range1 [m]	Azimuth1 [rad]	AZ_angle [°]	Amplitude	Speed_Radial [m/s]	CL_THR_Level	Object_(
0	20.58	0.005584	0.32	63.04	-0.26	16.96	0
1	43.89	-0.008376	-0.48	54.72	-0.2	16.96	0

FIGURE 8: IRV Onboard software GUI

This software is designed to log and filter objects that are identified by the radar into different object classifications. Each of the objects is logged in coordinates of X_{point} and Y_{point} which identify the exact location of each object relative to the IRV over time. For example, in Table 2 the position for the object in sample data 1 is 15.456m in front and 1.264m to the right from the center of the IRV. Knowing the exact positions of the objects being logged, the IRV can determine both velocity and the acceleration of objects in the x-direction by taking the derivative. The raw targets of the sensor are shown in the target viewer window as circles. All of the CAN data can be logged for future analysis.

One of the major motivations for developing the IRV is to improve modeling and simulation of car-following behavior. The data from the UMRR and the speed sensor are compiled and shown in Table 2. The radars report the coordinates (X_{point}, Y_{point}) and (X_{speed}, Y_{speed}) from the center of the radar for each object in view to provide the distance and the speed between the IRV and the forward vehicle. Longitudinal acceleration is also reported to indicate whether or not the IRV is approaching the forward vehicle, as well as the direction of movement with positive or negative values of this acceleration. The speed sensor uses GPS and onboard algorithms to interpolate the speed and position data. The 'time since midnight' variable is obtained from the satellites and is used as the time sync for all data being logged for the IRV. The speed sensor records the speed, heading, latitude, and longitude as the vehicle is in motion at a rate of 10Hz.

An accurate measurement of the IRV speed is recorded in km/h and is determined through the Doppler shift. Lateral acceleration is calculated by velocity squared divided by radius of turn, which provides the centrifugal forces applied to the vehicle during left (negative) or right (positive) turns/curves. Longitudinal acceleration provides the forces applied to the vehicle during acceleration (positive) and breaking (negative). All of the data is extracted from the software to a comma separated file (*.csv) where any program that can open this file type can be used for opening and preparing the data.

TABLE 2: List of Variables and Sample Data Collected from the Instrumented Vehicle

	Variable	Sample Data 1	Sample Data 2
RADAR DATA	**Object ID**	0	0
	Time [s]	00:33:50:560	00:33:50:686
	Object Number	1	1
	x_Point [m]	15.456	14.976
	y_Point [m]	1.264	0.832
	Speed_x [m/s]	-0.2	0.2
	Speed_y[m/s]	0.7	-1.2
	Acceleration	0.33	1.4
SPEED SENSOR DATA	**Time Since Midnight**	47767.8	47767.9
	Speed [km/h]	88.50708	88.98859
	Heading [°]	137.01	137.08
	Latitude [°]	38.90401	38.904
	Longitude [°]	77.09206	77.09205
	Latitude Minutes	2334.241	2334.24
	Longitude Minutes	4625.525	4625.524
	Altitude [m]	15.75	15.93
	Radius of Turn	270.1	270.1
	Longitudinal Acceleration	0.53	1.17
	Lateral Acceleration	-1.9	-1.43

The design of this IRV and data acquisition system provides researchers with an advanced tool for collecting car-following data. As this research focuses on the Wiedemann model, the data from the IRV will assist in the calibration of certain threshold values in the car-following algorithm from different drivers. The variables $\left(X_{\text{point}}, Y_{\text{point}}\right)$, $\left(X_{\text{speed}}, Y_{\text{speed}}\right)$ and longitudinal acceleration will be used in this effort to calibrate headway time, following variation, negative following threshold and positive following threshold which are part of the Wiedemann model. This IRV will be driven through the LL set up along a freeway work zone to capture the change in car-following behavior from normal freeway conditions.

DEVELOPMENT OF CMTS SYSTEM

The LL concept emphasizes the importance of having a natural environment in the real world as the foundation for the experiment. In support of the environment for this case study, a system was designed to provide connectivity, interoperability, and data processing of the natural real life setting. The data requirements needed to support this case study include collecting: volume, speed, occupancy, headway, travel time, and video data. The development of a Connected

Mobile Traffic Sensing (CMTS) system is designed and built to meet the requirements for data collection and connectivity within the LL.

The CMTS system is a portable roadside trailer that is equipped with batteries and solar panels which are used to support the power needs of the onboard equipment. The technology components that make up a CMTS system include: onboard computer, cellular modem, network router, GPS, Bluetooth traffic sensors, Internet Protocol (IP) dome cameras, roadside unit (RSU), and microwave radar sensor.

The following provides a summary of the technology selected to support this LL when collecting work zone data in the real-world environment:

1. GPS is used to determine location of CMTS units in relation to work zone
2. Bluetooth sensors are used to collect travel time data within the LL limits of the work zone
3. IP dome camera is used to record video of work zone geometry, work intensity, etc.
4. Microwave radar is used to collect speed, volume, occupancy, classification, headway, and gap data
5. RSU is used to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) transmission of traffic information through dedicated short range communication (DSRC).
6. Cellular modem is used as communication protocol which provides connectivity to the onboard computer and manages the transmission of data back to Saxton Transportation Operations Laboratory.

These CMTS systems are placed along the freeway in the LL to collect real-time operational performance data needed to conduct the study. There are several different nonintrusive devices that can be used to collect traffic data that are off-the-self technologies. Microwave radar devices are acceptable technologies used for collecting traffic data. When tested alongside other manufactures' products, they provide a detection rate accuracy of 92.8% with a mean absolute percent error of 5.5% *(27)*. This allows researchers to non-intrusively collect traffic data safely in the field by not disrupting the natural environment and allows the system to provide real-time connectivity of the LL, enabling remote connections and data transmission to a laboratory or traffic management center.

Determining the location of the LL specific to a freeway work zone is centered on the research objective. Identifying the laboratory environment within society that fits the requirements involves partnering with the local transportation authorities. For this case study, the location was selected along I-95 in Virginia through coordination with the Virginia State Department of Transportation (VDOT) and Federal Highway Administration (FHWA). The geometry of the road and surrounding environment were taken into consideration as these may influence the drivers' behavior (e.g., sight distance). The placement of the CMTS systems along the limits of the LL is essential for developing the connected environment to collect data of the natural setting. Once the boundaries of the LL have been established, the experiment for collecting data on driver behavior can begin.

Two data streams are being collected in this case study; IRB and CMTS. The data collected in the LL is sent through a cellular modem from the field location to a server in the Saxton Transportation Operations Laboratory. The data logged onboard the IRV during the driver subject trips is very large, therefore it has to be extracted and saved to the server from each individual driver experiment manually. The IRV can be set up to support Vehicle-to-Infrastructure (V2I) while the CMTS system collects data as the vehicle passes through the LL directly, or the IRV can transmit the data through a higher speed cellular modem directly. The design of the data transfer in the LL must be carefully designed based on the needs of the experiment.

SUMMARY AND CONCLUSIONS

This paper describes the concept of a Living Laboratory applied to transportation operations research through a case study on capturing driver behavior in a freeway work zone. The living laboratory concept enables researchers to conduct research in a natural, real-world environment to promote collective learning and collaborative research based on user-centric innovations for evaluating operational performance. After deployment, an LL provides an active research environment for longer term studies and evaluations of concepts along live roadways to obtain richer datasets to assist in accurate results. This is one of the key factors that separate the LL form typical data collection methodologies. One of the objectives of this case study is to demonstrate the concept of a LL applied to a freeway work zone. Using the application of a LL and tailoring this concept to collect car-following data from drivers to optimize the thresholds of the Wiedemann model is presented. Two objectives were identified for the development of this LL: (1) collecting scientific measurements of car-following behavior from a driver in a natural environment, and (2) obtaining relevant data (e.g., traffic conditions) of the natural real life environment within the LL.

The design and development of an Instrumented Research Vehicle (IRV) is described in this case study. A sample of data collected from this IRV was presented and explained thoroughly in this paper to prove success of this new and innovative vehicle experimental design. This robust and smart instrumented vehicle design has broad potential of being utilized in various driver behavior studies. More specifically, this in-house built instrumented vehicle is ideal for studying driver interaction and behavior through freeway work zones which are hot spots for operational and safety problems. Clearly, there are many lessons to be learned from these types of experiments which utilize this specially designed vehicle.

The integration of radar technology and GPS provided precise collection of unconscious speed oscillations that can be collected from different drivers. The IRV proved effective in collecting the data needed to calibrate headway time (CC1), following variation (CC2), negative following threshold (CC4), and positive following threshold (CC5) amongst different drivers.

The design and development of Connected Mobile Traffic Sensing (CMTS) systems are described in this case study. The integration of state-of-the-art ITS technologies such as non-intrusive equipment, supports the LL environment by providing the connectivity, interoperability and data processing of the natural real life setting. Site selection of the LL is dependent on research objective and should be in coordination with local transportation authorities. The site selected in this case study was selected in a freeway work zone along I-95 in Virginia.

The use of LLs and an experimental platform for real-world environments is shown to be an effective method in this case study. The same methodology for setting up a LL can be used for various studies in transportation operations and connected vehicle research.

REFERENCES

1. Markopoulos, P., and G. W. M. Rauterberg, (2000). Living Lab: A White Paper. IPO Annual Progress Report 35, 53-65.

2. Ballon, P., J. Pierson, and S. Delaere, (2005). Open Innovation Platforms for Broadband Services: Benchmarking European Practices. *16th European Regional Conference*, Porto, Portugal.

3. Eriksson, M., V. P. Niitamo, and S. Kulkki, (2005). State-of-the-art in Utilizing Living Labs Approach to User-centric ICT innovation - a European approach. *Centre of Distance Spanning Technology*, Luleå University of Technology, Luleå, Sweden.

4. Core Labs. (2007). Living Labs Roadmap 2007-2010: Recommendations on Networked Systems for Open User-Driven Research, Development and Innovation. *Centre of Distance Spanning Technology*, Luleå University of Technology, Luleå, Sweden.

5. Bergvall-Kåreborn, B., and A. Ståhlbröst, (2011). Living Lab: An Open and User-Centric Design Approach. *Information and Communication Technologies, Society and Human Beings: Theory and Framework,* Chapter 16, 190-208. Hershey, PA

6. Testbed (2012). Wikipedia: The Free Encyclopedia. Wikimedia Foundation, Inc. Retrieved January 2013. <http://en.wikipedia.org/wiki/Testbed>

7. Wiedemann, R., and U. Reiter, (1992). Microscopic Traffic Simulation. The Simulation System Mission. *University Karlsruhe*, Karlsruhe, Germany.

8. Lownes, N., and R. Machemehl, (2006). Sensitivity of simulated capacity to modification of VISSIM Driving Behavior Parameters. *Proceedings of the 85th Transportation Research Board Annual Meeting,* Washington D.C., USA

9. Gomes, G., A. May, and R. Horowitz. (2004). Congested freeway Microsimulation Model Using VISSIM. *Journal of the Transportation Research Board,* 1876, 71–81.

10. Boyce, T., and S. Geller, (2002). An instrumented vehicle assessment of problem behavior and driving style: Do younger males really take more risks? *Accident Analysis and Prevention*, 34, 51–64.

11. Ma, X., and I. Andreasson, (2006). Estimation of Driver Reaction Time from Car-Following data: Application of the Evaluation of Genera Motor-Type Mode. *Journal of the Transportation Research Board*, 1965, 130-141.

12. Ghazavi, P., A. Zavabeti, and M. Sarvi, (2009). Development of New Driver Behavior Model: Part 1 Development of a Platform to study Car-Following Behavior Using Real Time Data. *Paper presented at the Transportation Research Board Annual Meeting,* Washington D.C., USA.

13. Nowakowski, C., S. Shladover, D. Cody, and F. Bu, (2010). Cooperative Adaptive Cruise Control: Testing Drivers' Choices of Following Distances. Report No. UCB-ITS-PRR-2010-39. *California PATH Program*, Richmond, CA.

14. Valero-Mora, P., A. Tontsch, I. Pareja-Montoro, and M. Sánchez-García, (2010). Using a Highly Instrumented Car for Naturalistic Driving Research: a Small-Scale Study in Spain. PROLOGUE Deliverable D.3.5. *INTRAS/University of Valencia*, Valencia, Spain.

15. Lehtonen, E., O. Lappi, and H. Summala, (2012). Anticipatory eye movements when approaching a curve on a rural road depend on working memory load, *Transportation Research Part F: Traffic Psychology and Behavior*, Vol. 15, 369–377.

16. Zhang, J., K. Zhang, R. Grenfell, and R. Deakin, (2006). On the Relativistic Doppler Effect for Precise Velocity Determination using GPS. *Journal of Geodesy*, Vol. 80, 104-110.

17. United States Coast Guard. (1996). NAVSTAR GPS User Equipment Introduction. Washington, D.C. USA.

18. Jiang, Y. (2007). Traffic Capacity, Speed, and Queue-Discharge Rate of Indiana's Four-Lane Freeway Work Zones. *Journal of the Transportation Research Board*, 1657, 10-17.

19. Pesti, G., D. R. Jessen, P. S. Byrd, and P. T. McCoy, (2007). Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy. *Proceedings of the 78th Transportation Research Board Annual Meeting,* Washington D.C., USA.

20. Kim, T., D. J. Lovell, and J. Paracha, (2000). A New Methodology to Estimate Capacity. *Paper presented at the Transportation Research Board Annual Meeting,* Washington, D.C., USA.

21. Benekohal, R. F., A-Z Kaja-Mohideen, and M. V. Chitturi, (2003). Evaluation of Construction Work Zones Operational Issues: Capacity, Queue, and Delay. Report No. ITRC FR 0/01-4. *Illinois Transportation Research Center*, Illinois Department of Transportation, Champaign, IL.

22. Sarasua, W. A., W. J. Davis, D. B. Clarke, J. Kottapally, and P. Mulukutla, (2004). Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures. *Journal of the Transportation Research Board*, 1877, 85-94.

23. Meinecke, M. M., and H. Rohling, (2000). Combination of LFMCW and FSK Modulation Principles for Automotive Radar Systems. *German Radar Symposium*, Berlin, Germany.

24. Rohling, H., and C. Moller, (2008). Radar waveform for automotive radar systems and applications. *Proceedings at the IEEE Radar Conference*, Rome, Italy.

25. SmartMicro. (2012). UMRR Automotive Sensor Data Sheet Type 30. Retrieved from http://smartmicro.de/images/stories/contentimage/automotive/UMRR%20Automotive%20Type%2030%20Data%20Sheet.pdf

26. SmartMicro. (2012). UMRR Automotive Sensor Data Sheet Type 29. Retrieved from http://smartmicro.de/images/stories/contentimage/automotive/UMRR%20Automotive%20Type%2029%20Data%20Sheet.pdf

27. Grone, B. (2012). An Evaluation of Non-Intrusive Traffic Detectors at the NTC/NDOR Detector Test Bed. *University of Nebraska- Lincoln, Civil Engineering Theses, Dissertations, and Student Research.* Paper 47.