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An Online Prediction System of Traffic Signal Status for Assisted Driving on Urban Streets:

Pilot Experiences in the United States, China, and Germany

By Thomas Bauer, P.E., PTOE, Jingtao Ma, Ph.D., P.E., and Frank Offermann, Ph.D.

Stop and go movements on urban streets under traffic signals are the sources of increased fuel consumption, vehicle wear and tear, commuter anxiety, and thus safety risks. When approaching or stopping at a signalized intersection, if a driver or in-vehicle computers can be assisted with traffic light state and switching information, many of these side effects can be greatly alleviated.

One Connected Vehicle (CV) technology—Eco-approach and departure, or Green Light Optimal Speed Advisory (GLOSA)—aims to alleviate these side effects by presenting the information via in-vehicle human-machine-interface (HMI), or engine management. A few forms of such applications and their car manufacturers include:

- Recommended speed to cruise through a green signal (Audi, Honda, BMW);
- Warning message to release gas pedal of oncoming red light (Honda);
- Red countdown timer to remind resuming driving in time (Honda, BMW); and
- Tied engine management to stop engine for a known long wait ahead and restart right before the light turns green (Audi).

The photos in Figure 1 illustrate examples of two car manufacturers' HMI designs for presenting the information.

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Figure 1. Examples of in-vehicle human machine interface designs that present traffic signal data to drivers: (top-a) red countdown dial or speed advice together with navigation display in the central control (BMW) (bottom-b) red countdown timer or speed advice on digitalized dashboard (Audi).

For its many potential benefits, simulations and lab experiments were set up to design algorithms for computing optimal cruise speed when approaching a traffic signal.[1,2,3] Traffic flow simulators were applied to combine with vehicle emission and fuel consumption models to examine variables such as congestion levels, vehicle types, and throttle controls.[4]

Test fields of various scales helped demonstrate and evaluate the eco-approach and departure systems among other CV applications. The U.S. Department of Transportation (USDOT) initiated a number of test beds that installed road side units (RSU) and vehicle on-board units (OBU) in addition to traffic management centers enhanced with communication modules to RSUs and OBUs.[5] For example, in Novi, Michigan, USA, 50 installed RSU can broadcast signal phasing and timing (SPaT) messages to equipped vehicles for eco-approach and departure tests. One large scale field test Sim^{TD} (Safe and Intelligent Mobility–Test Field Germany) was also set up in Frankfurt, Germany to evaluate different vehicle-to-infrastructure (V2I) technologies, including GLOSA in urban environments.[6] Results showed that when fully deployed, GLOSA can help reduce carbon emissions from vehicle traffic by up to 15 percent, and annual gas savings can reach 245 million gallons in Germany alone. Small scale corridors are also equipped similarly to demonstrate similar V2I applications.[7,8]

When it comes to delivering signal phasing and timing messages to vehicles, current practice sees three major methods: field communication via dedicated short-range communication (DSRC); infrared, signal management system backhaul network to relay with vehicles; or computer vision inside vehicles to recognize traffic signal and color changes. DSRC is the default method in most lab experiments and test fields for its sub-second low latency of data exchange between cars and traffic lights, which also makes other applications such as collision avoidance possible. However, the retrofit of existing infrastructure to accommodate DSRC communications is costly considering the number of existing traffic signals. For example, an earlier benefit-cost analysis estimated 27.3 billion dollars for a nationwide upgrade to urban freeway and intersections in the United States in a five-year period.[9] Represented by Google's self-driving cars, another method of traffic signal data stream into cars is using cameras to capture signals, analyze their current color, and make corresponding continue-driving or stop decisions.[10] Some research even developed iPhone apps to continuously capture traffic light switches and then predict timing schedules from analyzing signal switching time and patterns.[11]

Another approach is to harness advances in 3G/4G or Long-Term Evolution (LTE) wireless communications. The traffic signal data is collected by tapping into existing signal management systems (SMS) in a read-only or one-way data flow, adding signal prediction and then relaying to the cars via 3G/4G or LTE. A pioneering project, "Travolution," saw collaboration between the City of Ingolstadt, Germany and Audi to complete the data flow circle using cellular communications.[12] Later similar demonstrations followed the same path, including a large scale deployment in Berlin, Germany, where 700 signals have already been connected to the Audi backend and then target data were sent to a car fleet driving in the city.[13]

This paper describes an online signal state prediction system, dubbed Personal Signal Assistant (PSA), which must work with agencies' SMS for data collection and then prediction. At the 2014 Consumer Electronics Show (CES) in Las Vegas Nevada, USA, the system supplied signal prediction data to one Audi car and demonstrated the technology. It received the "Best Auto Tech" award from The Verge for being considered the most potential connected vehicle technology that can be deployed in the near future. This report introduces the system architecture, shares field test experiences in Las Vegas and other cities in China and Germany, and discusses a potential deployment roadmap for North America.

Online Signal State Prediction System Architecture

The developed signal state prediction system, Personal Signal Assistant or PSA, produces for each signal group second-by-second prediction of two signal state switches in a full cycle: time to green (TTG) and time to red (TTR). The 1 Hz data rate allows for quick updates and fast responses when the traffic situation changes. For example, when transit signal priority or emergency preemption calls occur, the PSA system can quickly generate the corresponding message. The system consists of three major sub-systems: signal state data collection from field controllers via signal management systems; signal state prediction; and prediction data relay to vehicles or smart phones, as depicted in Figure 2.

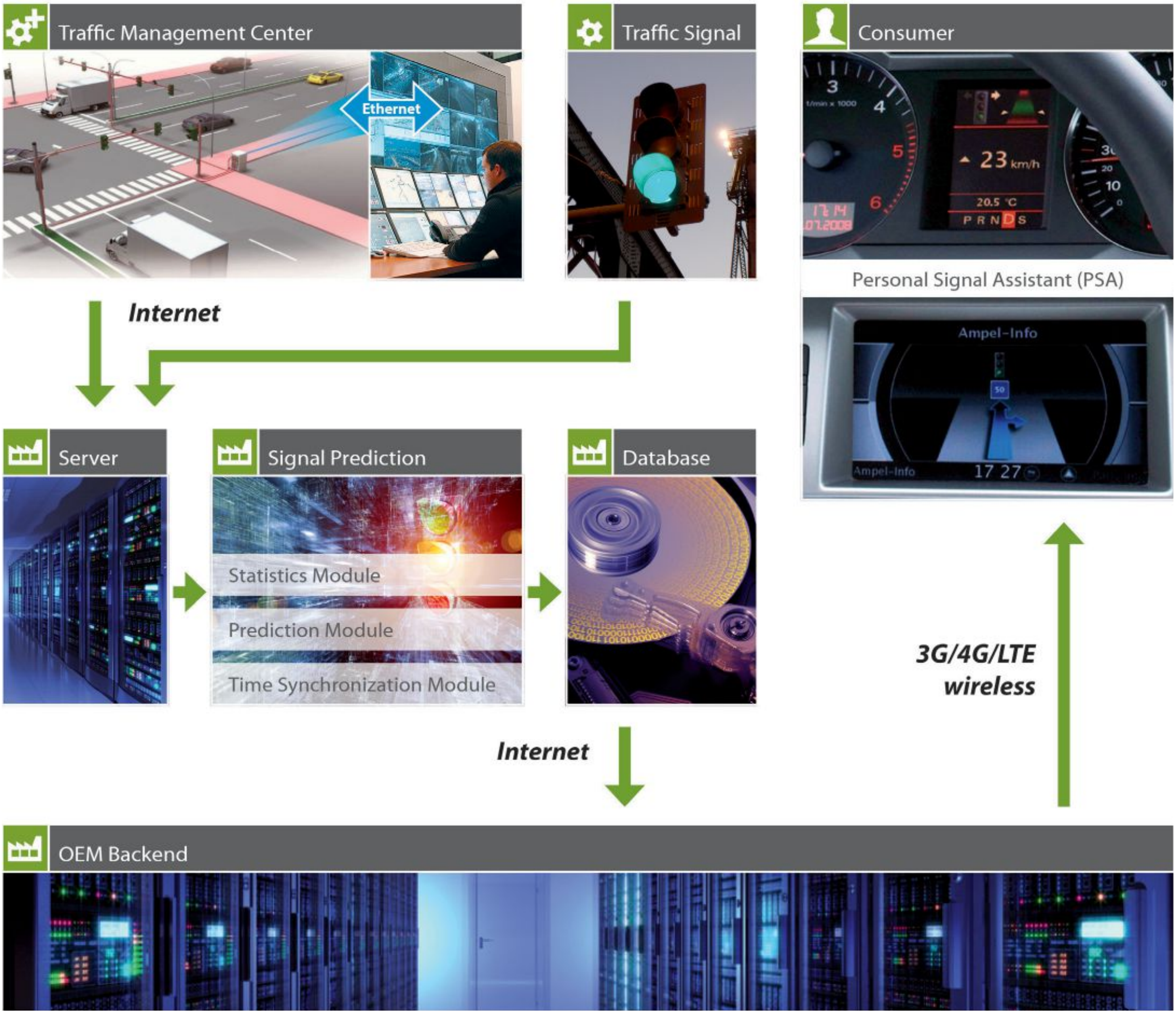

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Figure 2. System architecture and data flow of the online signal state prediction system.

Traffic Signal Data Collection

Tied to the signal management system (SMS), the traffic data collection module streams necessary data in real time to the prediction engine.

Signal State Prediction

Signal state prediction lies at the core of the PSA. This is accomplished by a proprietary and patent-pending technology that analyzes both historical patterns and current traffic conditions including vehicle actuations and signal priorities or preemptions, to provide the best estimate of future signal state change times. Real-time data fusion becomes crucial for traffic-actuated controls because the signal timing adjusts according to different traffic arrival patterns.

Data Relay

After TTG and TTR data are generated, these data are formatted in a light-weight package and sent to the consumers, e.g., telematics or navigation service providers, or the backend server system of car manufacturers who then send the data via wireless network into the car HMI and possible engine management. One critical issue in the data relay is the compensation for all possible time lapses at each step in this data chain. For example, the compensation could include the latency of data transmission from field controller to SMS, collecting time from SMS to the prediction system, computing time, and forwarding times. All timestamps must be carefully analyzed and latency compensated for in the final delivery to drivers or engine management.

Field Demonstration and Results

Customized PSA systems were tested in field deployments in the United States, China, and Germany. These test field conditions varied greatly in their control logic complexities, driving behavior, and traffic conditions—all affecting the prediction data quality.

The most notable of these deployments is set along Las Vegas Boulevard ("The Strip"), where signal controllers are programmed with an array of time-of-day actuated-coordinated timing plans to handle traffic streams of private vehicles, tour buses, hotel and casino service vehicles, and pedestrians. Control timing plans are also often adjusted for special events such as concerts or shows. Meanwhile, test area signal controllers were supplied by two different vendors, Siemens and TrafficWare, where PSA data collection must cope with both standard NTCIP protocols and other proprietary communication protocols. This prediction system deployment supported Audi's Traffic Light Info Online system demonstration at the 2014 Consumer Electronics Show where it received high media acceptance.[14,15,16]

Other field test conditions are less complex than Las Vegas; however, they feature different control logic and unique local conditions. Figure 3 shows all sites and their main characteristics.

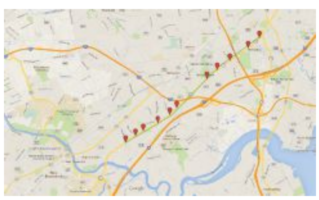
Test Sites location	Characteristics
Las Vegas, Nevada, US 	• 50 intersections • Siemens and TrafficWare controllers • Semi-actuated control, with protected/permissive and overlap phases • Las Vegas Boulevard between Mandalay Bay and Sahara Avenue ("The Strip"); Paradise Avenue, and all signalized intersections within this area as well as seven intersections along Flamingo St to The Palms Hotel. • Continuous running; field demonstration with Audi AG (January 2014)
Shanghai, China 	• 14 intersections • Two local controller vendors • Time-of-day fixed control, with protected/permissive phases • Frequent timing plan updates for changing traffic conditions • Test route near Tongji University Jiading Campus and three on-campus signals (not shown in map to the left) • Field demonstration with Audi AG (November 2014)
Dortmund, Germany 	• One intersection • Siemens controller • Semi-actuated control running TRELAN and compiled for TL • Proof-of-concept: prediction system ran on archived signal state and vehicle detection data • Location: Südwall – Ostwall / Kleppingstrasse – Ruhrallee
Merzig, Germany 	• 4 intersections • Swarco ACTROS controllers • Semi-actuated control with transit priority • Control logic in LISA+ of Schlothauser and Wauer and thus in OML • Scheduled field test in May 2015 • Data streamed to a fleet of the Car2Saar testbed • Gaswerk / Lothringerstrasse; Hochfallstraße / Bauerstraße; L174 / Lothringerstraße; Rieffstraße / Lothringerstraße
US Route 1, New Jersey 	• 11 intersections • TrafficWare controllers • Semi-actuated control • High speed travel corridor with large trucks posing safety risks for trailing vehicles • US Route 1 from Plainfield Ave to Green St • Lab test and field demonstration with BMW Group

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Figure 3. Test field location setup and signal controls

Evaluation of Prediction System Performance

Within the context of eco-approach and departure applications, the prediction system performance is evaluated by two aspects: communication latency of TTG and TTR data that its consumers—drivers and vehicle engine system—can immediately sense, and prediction accuracy of the output TTG and TTR data.

A number of factors can get in the way of timely data transmission to the vehicle. The foremost factor is the time between a field controller event, e.g. vehicle actuation, and its notification to the traffic management center and later the prediction system. After this time lapse is correctly compensated, other time lapses can be sequentially time-stamped and compensated equally well. These factors include prediction algorithm run time and data relay time to vehicle dashboard or engine management. In the Las Vegas field tests, vehicle trajectory logs indicated that this overall latency, from receiving the data to the vehicle display, was between 2 and 3 seconds. The value is characterized in milliseconds and calibrated for the final system acceptance.

For its dynamic nature, signal states are predicted every second for each signal groups. Evaluation of the prediction quality can be conducted each time step. For example, if on a certain day at 10:28:06 AM, the system predicted a particular phase will change to green (TTG) in 30 seconds, while the actual phase change occurred at 10:28:38 AM, then the prediction error at the time step of 10:28:06 AM was 2 seconds (early). On the other hand, if the actual phase change occurred at 10:28:35 AM, then the error was -1 second (late). For a deployment system, the prediction quality must be continuously maintained at satisfactory levels.

In the developed prediction system, various quality monitoring modules were set up to track the quality changes. For example, one of the quality monitoring services is the so-called "green-funnel" chart, as shown in Figure 4.

In Figure 4, the x-axis represents the prediction horizon (cutoff at 90 seconds), i.e., the timestamp before the actual signal switches. The y-axis represents the percentage of each prediction error range by the following color schemes: the dark green (in the middle of the color column) represents no prediction error, and each adjacent color change to both above and below represents one extra second of error. These can help analysts evaluate the trend of error ranges, and improve the prediction system. In all field demonstrations, the same quality standard was maintained throughout the test periods.

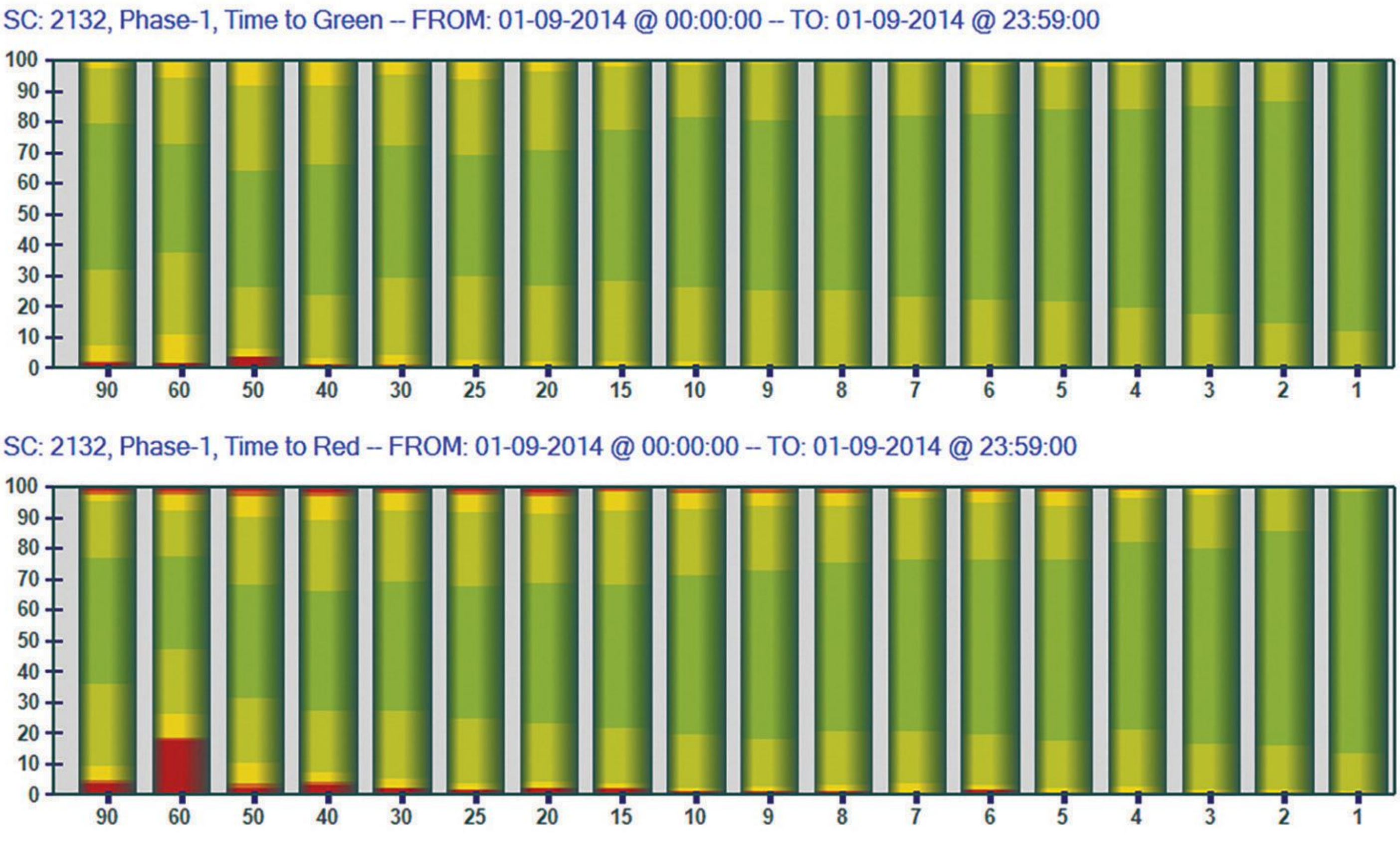

Figure 4. Green-funnel chart to visualize signal state prediction data quality for both time-to-green (TTG) and time-to-red (TTR) for one day. Color legend includes the following: with the dark green as no error and lighter green represents 1 second of error, each color change represents one extra second of error.

Images courtesy of Heusch Boesefeldt America

Figure 5. Field tests in Las Vegas, NV, USA demonstrated the quick responses of the prediction system and display in the test vehicle: (left-a) test vehicle approaching the empty left turn, the traffic light info online (TLIO) display on dashboard is blank; (right-b) once the test vehicle is detected, the prediction system is able to predict time-to-green and TLIO displays the countdown timer.

System Field Tests and Driving Experiences

Field tests have given the team valuable experiences from the unique combined perspective of developers, drivers, traffic engineers, and local agencies. In particular, field demonstrations in Las Vegas and Shanghai with the Audi vehicle equipped with the traffic light info online (TLIO) system clearly illustrated the safety and mobility benefits of an eco-approach and departure system.[17] For example, with TLIO, waiting at long signal cycles became a known period with the red countdown timer, and the auto-engine start at 5 seconds before lights turning green became a noticeable cue for drivers to focus on the road again. At the same time, test drivers were observed to follow speed advice from the system and avoided last-second sudden stops.

Safety benefits also became apparent during field demonstrations. When trailing behind large trucks or tour buses, drivers were informed of the signals ahead when their view was impeded. Similarly, the dashboard display of signals served as adequate substitute at situations of impaired sight distance by curvatures or slopes, for which Flamingo Road overpass of I-15 in Las Vegas provides an excellent example. Due to its slope, drivers cannot see the traffic signal until the vehicle reaches the aperture where it can become unsafe to stop. The dashboard display of countdown timer or the speed advice gave drivers a heads-up warning of situations ahead.

Additional advantages were also revealed in the field tests, such as vehicle actuations. Figure 4 shows the system functioning of one test vehicle making a left turn on southbound Las Vegas Blvd. When approaching the empty turn bay, the countdown timer is blank (Figure 5a), for without actuation the phase is not scheduled for the upcoming cycle. After the test vehicle passes the detector, the prediction system is immediately able to predict the exact time to green and thus the countdown timer display starts (Figure 5b). This gives drivers more confidence and sometimes relief, because waiting for more than 2 minutes (148 second countdown in this case) could lead a driver to the perception of malfunctioning signals and thus possible red light running.

Closing Remarks

As this Connected Vehicle application of eco-approach and departure has reached its maturity, the developed signal state prediction system provides the quickest way to bridge the gap between existing infrastructure and connected vehicle technologies. As shown in all test fields with extensive demo vehicle runs, this technical approach has proven its feasibility with the computing, communication, and vehicle technology existing today. Current large-scale city and region wide tests are expected to lead to imminent full-scale deployment.

Agency support is critical for the development of such eco-approach and departure systems. All of the mentioned field demonstrations would not have been successful or even possible without the support from the local agencies, namely Las Vegas Freeway and Arterial System of Transportation (FAST), Shanghai local traffic police, New Jersey Department of Transportation (NJDOT) and the City of Merzig, Germany. Understandably, all of these agencies were concerned with driver distraction possibilities of such connected vehicle technology; however, they became convinced by experiences gained from the demo systems. **itej**

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Thomas Bauer, P.E., PTOE *is the CEO of Heusch Boesefeldt America. He has 24 years of experience in the fields of intelligent transportation systems (ITS), traffic engineering, transportation planning, transit operations, and traffic software development. Most recently, Thomas has focused on Active Transportation Demand Management (ATDM) and Connected Vehicles applications and evaluations. He holds master's degrees in transportation engineering from Oregon State University and civil engineering from the University of Stuttgart, Germany. Thomas is a member of ITE.*

Jingtao Ma, Ph.D., P.E. *is lead engineer at Heusch Boesefeldt America. He has more than 15 years of experience in intelligent transportation systems (ITS), traffic engineering, and transportation planning. He specializes in real-time and multi-resolution traffic modeling and simulation and urban digital footprint analysis for transportation planning. He received his doctor of philosophy from University of California, Davis with his research on integrated corridor control that balances system efficiency and user fairness.*

Frank Offermann, Ph.D. *is the director for business development and vehicle-to-infrastructure (V2I) technology at Heusch/Boesefeldt. He has 18 years of experience in the fields of intelligent transportation systems (ITS) and traffic engineering, focusing on solutions for urban street and freeway operations. Frank has been involved in numerous research activities in the vehicle-to-infrastructure area and is now dedicated to the market introduction of cooperative systems. He received his doctor of philosophy in civil engineering from RWTH Aachen University, Germany in 2000 with his research focused on data fusion of floating car data.*