Spotlight

Vehicular Communication

EDITORS' INTRODUCTION

Researchers in both academia and industry are increasingly interested in vehicle-to-vehicle and vehicle-to-infrastructure communication, because they enable numerous safety systems and end-user applications. To gain a better understanding of vehicular communication, we solicited input from experts, interviewing Wieland Holfelder, vice president and chief technology officer of DaimlerChrysler Research and Technology North America, and Jean-Pierre Hubaux, a professor of communication systems at the École Polytechnique Fédérale de Lausanne. We also received short articles from Timo Kosch and Markus Strassberger of BMW Group Research and Technology and from Ken Laberteaux, Lorenzo Caminiti, Derek Caveney, and Hideki Hada of Toyota. Collectively, these four pieces indicate a growing momentum in vehicular communication, although many open questions remain.

—Keith Farkas, Liviu Iftode, and John Heidemann, guest editors

AN INTERVIEW WITH DAIMLERCHRYSLER'S WIELAND HOLFELDER

Vehicle-to-vehicle and vehicle-to-infrastructure communication seems to be an up-and-coming topic. What is this technology's potential?

Dedicated Short Range Communication, or DSRC, has the potential to significantly reduce accidents and improve traffic flow. So far, vehicles have been able to "feel" or "see" the environment through autonomous vehicle sensors such as wheel-speed sensors or radar and ultrasound systems. DSRC is the next logical step in vehicle safety, because it lets vehicles communicate with each other and with the infrastructure. It gives the vehicle systems and therefore the drivers a much better awareness of their surroundings so they can avoid dangerous situations altogether. We call this the "extended information horizon," which lets a driver "see" over hills and around curves.

Developing a new communication system exclusively for automotive use sounds like an expensive and difficult undertaking. Are other technologies such as wireless local area networks a valid alternative?

DSRC is actually based on wireless LAN technology and piggy backs on IEEE 802.11a, which operates in the adjacent frequency band at 5.8 GHz. However, DSRC will require some modifications for automotive use. IEEE 802.11p—also called Wireless Access for the Vehicular Environment—provides the required standardization for these modifications. For example, WAVE standardizes intelligent power management of the DSRC radio to achieve larger distances between vehicles while still being able to scale in a dense environment (such as at a toll plaza with hundreds of vehicles in a small area). WAVE also addresses priority management, so safety messages will always have the highest possible priority.

The overall idea is that despite some of the required modifications and extensions, we can leverage investments in the development of the consumer versions of 802.11 chipsets for the automotive version, saving cost and development time. DSRC is unique in its ability to support safety applications, but it will also support a broad range of other vehicle-to-vehicle and vehicle-to-infrastructure communications needs.

What are some of the most promising communication-based safety applications?

One promising example of an infrastructure-to-vehicle communication application is what we call *traffic signal violation warning*. This application attempts to reduce the number of vehicles running red lights by informing the driver of changes in the signal phase, warning the driver if the vehicle dynamics suggest it will enter the intersection on a red light. This application directly addresses about 2,300 fatalities a year in the US and is the first step in addressing the general problem of intersection safety.

An interesting example in the area of vehicle-to-vehicle communication applications is the extended electronic brakelight application. This application would send a message from a hard-braking vehicle to all following vehicles so they can warn their drivers to avoid collisions.

For many of these applications to be effective, they need to work not just between two Mercedes-Benz or two Chrysler vehicles but between vehicles from many different manufactures. Who else is working on this topic and how will this eventually be deployed?

You're right; this can't be a proprietary effort. In fact, DaimlerChrysler is working with all major automobile manufactures and the [US] Department of Transportation in the Vehicle Infra-

SPOTLIGHT

structure Integration Consortium. Together with many other industry partners, VIIC is trying to answer remaining technical and nontechnical questions to prepare for a large-scale deployment decision for a VII network in approximately three years. The general concept for a deployment model is a nationwide rollout of a DSRC roadside infrastructure, immediately followed by large-scale deployment of DSRC in the new vehicle fleet with long-term commitments by all parties to support the technology. This model provides early benefits for all parties, as well as the stability necessary to justify the investment.

Are there other applications beyond safety that the VII network can support?

While the primary purpose of DSRC and the envisioned VII network is safety, they can support mobility applications, transportation-system operation and maintenance, and even commercial applications, as long as they don't interfere with vehicular safety. Such applications include probe-based traffic data collection, traffic advisories and prediction, signal coordination and management, incident identification and management, vehicle diagnostics and software updates, probe-based mapping to support position-aware safety systems, fleet management, electronic tolling and funds transfer, and digital map updates.

Many of these applications aim to enhance the driving experience or improve driving safety, but couldn't they also overwhelm drivers with too much information? What can be done to lessen these applications' cognitive impact?

The value and acceptance of these applications as well as human-factors solutions for an appropriate driver-vehicle interface are critical for this technology's success and are the substance of ongoing research projects. Applications that want to interact with the driver—for example, to issue a warning message—might need to consider different factors, such as a driver's individual reaction time, current road conditions, or even the traffic surrounding the vehicle. Larger-scale field-operational trials will help us understand and address these issues prior to deployment.

In addition to safety, are there other vehicular computing areas that the research community should focus on?

Vehicular computing is a very wide field, but even in just the telematics domain, many interesting and challenging developments exist. Infotainment is undergoing a fundamental paradigm shift to become all digital, portable, downloadable, and wireless. The emergence of portable digital music and video players and portable navigation systems—along with the convergence of cell phones to become multifunctional devices that incorporate the capabilities of specialized devices—requires that automotive original equipment manufacturers rethink how they integrate such technologies into the vehicle.

Trying to play catch-up with the consumer electronics industry to provide all the latest features in the vehicle is almost impossible due to different life cycles. So, we must consider a new approach in which the model shifts from providing features and functions as part of the vehicle system to enabling the vehicle to seamlessly integrate devices with such features and functions—for example, via a wired or wireless gateway. We'll need to address a lot of interesting research questions regarding the required standards, protocols, physical interfaces, and software update mechanisms.

Vehicular communication has emerged in Europe, Japan, and the US, but some of the approaches are quite different. Are we going to compete or collaborate?

There is a clear trend to unify and collaborate between the regions. Global automobile manufacturers have an interest in worldwide solutions. For example, the automobile industry in Europe is looking for a similar frequency spectrum allocation as in the US so they can reuse the standards and technologies developed here. We're not quite there yet, but things are looking promising and the politicians in Europe realize the potential benefits of such an approach and the need for a dedicated frequency spectrum.

What is DaimlerChrysler's position with respect to vehicular communication and intelligent transportation in general? What research problems are you currently pursuing in your lab?

Our research organization has recently promoted the "Vision of Accident-Free Driving," and DSRC and a VII network are important enablers toward this vision. DaimlerChrysler is participating in many joint industry and government activities to further develop and deploy this technology and to bring its benefits to our customers.

Some open research issues we must solve include standardizing message sets, refining application algorithms, and designing the underlying communication protocol to allow for scalability. We're developing a specialized simulation environment in our lab that we can use with our real-world testing results to directly address some of these issues. There are many other activities, but we're confident that vehicle-to-vehicle and vehicle-to-infrastructure communication have the potential to play a significant role in the future of safe driving.

Wieland Holfelder is vice president and chief technology officer of DaimlerChrysler Research and Technology North America, Inc., where his group focuses on research and advanced engineering for audio and video, consumer electronics integration, connected navigation, vehicle relationship management, and vehicle-to-vehicle and vehicle-to-infrastructure communication. He received his PhD in computer science from the University of Mannheim, Germany. He's a member of the IEEE and IEEE Communications Society. Contact him at wieland.holfelder@daimlerchrysler.com.

AN INTERVIEW WITH EPFL'S JEAN-PIERRE HUBAUX

What are the major challenges for vehicular networking?

It's a long list. Vehicular communication is complicated because of the vehicle's speed, harsh radio channel conditions, and so forth. The interaction between the computers and drivers is very complicated to design, as is the security. Deployment is also a big issue. This will be the first time in history that cars will be able to interoperate.

Will we have different sets of standards in different countries, or is there a consensus toward a single standard? With cellular phones, for instance, multiple standards still exist in the US that can't interoperate.

I see in Europe an effort on the side of automakers and governments to reach a single standard through the C2C-CC (Car-to-Car Communication Consortium). There are similar consortia in the US and Japan. I think there is awareness that setting standards is a big issue, and it's still a bit early to confidently predict whether the unfortunate situation that we have for cell phones will repeat itself or if it will be the more happy case of a single standard like in wireless LANs with IEEE 802.11. But competition will probably be less severe with vehicular communications than it was for cellular networks: vehicular communication is always going to be an addition to the main product, which is the vehicle itself, so I'm optimistic.

Will vehicular networking lead just to a better driving experience or to automated cars?

To begin with, it will just provide additional information to the driver. We probably won't see fully automated driving in our lifetime, but maybe with future work, more sophisticated things can happen. Yet jamming is a severe concern: it's virtually impossible to rule out jamming of a radio signal, so what happens in that case? You have to cope with the possibility that the signal doesn't go through, which means that you have to rely on the driver.

What will be the most promising vehicular computing applications?

Safety-enabled applications are really the ones that deserve all the attention and justify this effort. You have to remember that in Europe, for example, approximately 60,000 people are killed on the road each year, and 1.5 million people are injured. The most compelling applications relate to sensing and warnings about hazardous conditions, which can help drivers at night, in the fog, or during bad weather in the winter. Besides safety, there is a wealth of other possible applications, notably in e-commerce. They can be useful to bootstrap the whole business of vehicular communications.

Who should actually take the lead here, industry or universities?

Industry, I would say. The automakers have a crucial role to play, along with the equipment providers. Also, many issues will require government attention and contributions, and liability issues will eventually require connections between the technology and law enforcement. Universities should play their usual role of research and education.

How would you relate vehicular communications with mobile ad hoc networks?

Ultimately, vehicular networking seems to be the most relevant incarnation of mobile ad hoc networks. This can lead to a shift in the research effort. Why focus only on ad hoc networking in general? There are already hundreds of papers published on that. Why not consider also solving a real and difficult problem, with fairly precise requirements, which can generate meaningful and very useful results?

What are the main instruments to evaluate research results in vehicular networking? The problem with simulations is that it's difficult to accurately simulate both the traffic and communication. However, without a good evaluation methodology, vehicular networking papers risk being perceived as immature and irrelevant.

Yes, you have to simulate the movement of the vehicles plus the wireless communication. Of course, this is heavy machinery, but we're in 2006 and we have computers that can cope with that. Real systems must cope with the harsh environment with a lot of metal around, difficult weather conditions, obstacles such as bridges, and so forth. They have to work in crowded and dense roads under these very difficult conditions and cope with the mobility. Yet there exist nowadays simulation environments that can represent that, but their scalability is still limited. There are also subtle issues such as the fact that each simulated vehicle must be aware of the driving direction of all neighboring vehicles.

But simulations are not enough.

I absolutely agree. Standard procedures must be developed for real road tests. To test point-to-point communication, you can do it with two cars. You equip those cars with communication capabilities, drive around, and make measurements. Of course, when all cars around will be equipped with vehicular technology, how do you cope with possible interference? That's a compelling challenge. There exist also sophisticated analytical models representing typical movement patterns of road vehicles.

Can you talk about interesting research and engineering work in designing and building vehicular networks?

Yes, particularly in networking because you can't just take an ad hoc protocol and use it for vehicle communication. Geocasting will probably be very useful in such a scenario. The vehicle's speed can vary from zero to about 150 KM an hour, if not more, so all this has to be considered when designing the network. There are papers that address

SPOTLIGHT

the physical, MAC, and network layers, but more work is expected for the transport and application layers.

Going back to deployment issues, will there be a combination of ad hoc and cellular 3G networking for vehicles on the road? Do you see a role for the 3G in vehicular networking applications?

Most probably yes, because vehicular networks can use the existing infrastructure. In developed countries, cellular towers cover most of the roads, so this can certainly help with information exchange. For example, if need be, 3G networks can help check the certificates of cryptographic keys or communicate certain data. Of course, who is going to pay for the communication is usually an open question, but I'm sure that eventually cellular operators will become interested in this area.

What do you expect to happen with respect to security research in vehicular computing?

Things are moving fast in this domain. Essentially, automakers are becoming aware that privacy is an important and complex security problem in vehicular networks. You can't just say, let me take that solution I have investigated for ad hoc networks and throw it at this problem. Here, the requirements are becoming clear, and they're different from anything that has been envisioned so far.

For example, the issue investigated in ad hoc networks is for cases where the network is either fully self-organized, so each node is its own authority, or for cases with a single authority. With vehicular networks, you have something in between, in the sense that there is an authority that isn't always available online. There is a severe privacy issue that wasn't addressed previously. There are questions related to the fact that the available spectrum is actually very limited.

Another issue is revocation of the cryptographic keys and of the related certificates. How do you revoke them in such a network, and who is entitled to revoke them, for example? These are tough questions.

All in all, there are a number of problems that are both practically relevant and intellectually novel and challenging. This is why we've launched a European project on this topic (see www.sevecom.org).

Finally, what research problems in vehicular networking are you currently pursuing?

Basically, our vehicular networking research is exclusively in security. We don't do communication aspects or routing protocols and so on, because the security issues are so exciting. On that front, we're focusing on key management, including key revocation, and, of course, privacy (see http://ivc.epfl.ch).

Jean-Pierre Hubaux is a full professor at EPFL (Swiss Federal Institute of Technology, Lausanne). His research activity is focused on wireless networks. He coauthored the soon-to-be published graduate textbook *Security and Cooperation in Wireless Networks*. He received his Dr-Eng. in electrical engineering from Politecnico di Milano, Italy. Contact him at jean-pierre.hubaux@epfl.ch.

HARNESSING MOBILE NETWORKS FOR DRIVER ASSISTANCE

Timo Kosch and Markus Strassberger, BMW Group Research and Technology

Today's driver information and assistance systems are mainly based on data from onboard sensors and broadcast radio channels. In the future, vehicles will feature wireless connections between them and to roadside infrastructures, leading to huge mobile, ad hoc, connected sensor networks (for more on such networks, see the "Related Web Sites" sidebar). They will be able to harvest data available in the immediate surroundings and from the road ahead that could provide high-precision knowledge about relevant traffic situations if interpreted and reasoned upon correctly. Our group at BMW Group Research and Technology focuses on such enhanced environment awareness, which lets drivers foresee critical driving conditions.

With timely driver notification and support, next-generation driver assistance systems will help further reduce accident and fatality rates. Using wireless communication, vehicles will also be able to manage traffic cooperatively in a self-organizing fashion.

Transmitting critical messages

Active and preventive safety applications must be reliable and work correctly under all circumstances. That means that critical messages must be securely transmitted with high reliability and very short latency. Even with IEEE 802.11p and IEEE 1609 standardization under way, from a manufacturer's perspective, a variety of important questions have not yet been answered in a satisfactory manner—such as those on congestion control or on reliable and trustworthy low-latency transmission in an order of magnitude of 10 to 100 ms.

The requirements on the timeliness of the information stems from the necessity that driver-assistance systems only have accordingly small time windows to decide on a driver warning. Considering that vehicles typically travel at speeds of up to 15-20 meters per second in inner city areas, it's necessary to react within a few milliseconds in order not to loose too much valuable distance in critical situations. With many dozens of vehicles transmitting information in intervals of around 100ms in certain situations (such as at intersections) and the intrinsic hidden station problem, effective congestion control is crucial, too.

With network resources scarce, congestion control is inevitable, but we still need to ensure that that the most valuable data is transmitted. As opposed to existing fair channel access mechanisms, which assume a benefit in resource usage for the sender, data transmission on the road often doesn't provide any value to the sender but rather to the receivers (who might benefit from receiving information about an icy road, for example). Therefore, we follow an altruistic communication approach that considers the message's relevance to the receiver and embodies *controlled unfairness*—a means to avoid congestion while ensuring transmission of the most useful data.

Data integrity

Another important area where a viable and feasible solution still hasn't fully taken shape, despite many promising concepts, is ensuring the transmitted data's integrity and trustworthiness while protecting the data provider's (or networked vehicle's) privacy. We need to ensure full privacy under any circumstances, meaning no one can track our customers, derive their current condition, or disclose their identities. This is difficult, because receivers must be able to fully rely on a received beacon containing another vehicle's position—intruders shouldn't be able to fake such messages. At the same time, the sender usually has no interest in disclosing his or her identity, avoiding, for example, road-side network sniffers that can infer route patterns or driving habits.

We therefore push the development of both fault-tolerant cooperative applications and secured networks. We've considered several different concepts, including noninteractive zero knowledge protocols, Diffie-Hellman key exchange, use of pseudonyms, (anonymized) reputation systems, and trust management methods. However, note that driver assistance applications usually need to know other vehicles' positions and trajectories with a maximum tolerable delay of a few milliseconds—while cryptographic methods often consume calculation time that exceeds this tolerable latency.

Innovative safety applications

Even with solutions at hand for problems that concern all vehicle manufacturers, we still need standardization. Although progress has been made, we view this as a major stumbling block. However, as soon as all involved stakeholders develop a working vehicle communication system, the single manufacturer faces a surge of available data that promises many innovative functions—and certainly will be a field where different manufacturers will compete.

A decisive factor for a system's success will be whether the vehicles can deal with different levels of uncertainty, correctly interpret the data, draw the correct conclusions, and provide the driver with the right information in a meaningful way. The approach we're taking is to unobtrusively support the driver, especially in critical situations.

Consider the situation in figure 1, which shows a prototype system we're developing. Wireless communication penetrates solid objects to provide information beyond the vehicle's line-of-sight, in this case detecting the motorcycle that—prior to suddenly hitting its breaks—was hidden behind the white van. Before the system can warn the driver, it must verify the information, because it's unacceptable to distract or warn the driver with false information. After verification, the time window for driver notification is short; nevertheless, our prototype system typically warns the driver in time, as is the case in figure 1 (the driver can slow down to prevent hitting the motorcycle).

The motorcycle, for that purpose, frequently transmits its position and speed so surrounding vehicles can compute its corresponding trajectory. It also initiates event-based messages, in this case an emergency brake's deceleration values. The van following the motorcycle must swerve to avoid a collision, but our prototype vehicle receives information about its proximity to the motorcycle, showing the motorcycle's location in its central display and the head-up display. The system matches the incoming information with its vehicle's position, speed, and heading, taking into account digital map information and modeled driver behavior. When the motorcyclist brakes, the system concludes this is a critical situation, so it warns the driver acoustically.

To derive such a stable and reliable picture of a driving situation to come, a system must uniformly process information from a variety of different vehicles, locations, and sources (for exam-

RELATED WEB SITES

Network research

IEEE Vehicular Ad Hoc Networks Workshop: www.sigmobile.org/workshops/vanet2006

Network On Wheels project: www.network-on-wheels.de

Initiatives

CoMeSafety: www.COMeSafety.net

Vehicle Infrastructure Integration: www.its.dot.gov/vii

Car 2 Car Communication Consortium: www.car-to-car.org

European PReVENT's Willwarn project: www.prevent-ip.org/en/prevent_subprojects/safe_speed_and_safe_following/willwarn

Crash Avoidance Metrics Partnership: www-nrd.nhtsa.dot.gov/departments/nrd-12/pubs_rev.html
(CAMP comprises BMW, DaimlerChrysler, Ford, GM, Honda, Nissan, Toyota, and Volkswagen and works with the National Highway Traffic Safety Administration)

The Cooperative Intersection Collision Avoidance consortium: www.its.dot.gov/cicas/index.htm

The Advanced Safety Vehicle project: www.mlit.go.jp
(The ASV is a partnership between Japan's 14 automobile, truck, and motorcycle manufacturers, sponsored by the Japanese Ministry of Land, Infrastructure, and Transport.)

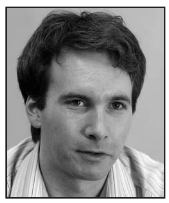
SPOTLIGHT

Figure 1. Early driver warning in a critical motorcycle traffic scenario.

ple, telematics service providers) and integrate it into a comprehensive model of the current and future driving context. (The European WILLWARN project, mentioned in the sidebar, examines wireless local danger warning systems in depth.)

For this model, we need to efficiently organize the accumulated spatiotemporal information. Using digital maps, we can effectively match incoming georeferenced information with road segments. We're also concurrently developing and analyzing fuzzy logic systems, Bayesian networks, and neural networks. Using probabilistic networks lets us exploit spatial and temporal dependencies and build on a variety of information from different sources to derive a reliable picture of the driving context. In addition, the networks support privacy issues, because they don't require unambiguous identification of the information originator.

Intelligent vehicles are on their way to comprehensively deriving their current and future driving context, thereby supporting their drivers in complex traffic situations. Wireless communication is the key technology for providing and sharing the necessary situational information. Processing the huge amount of possibly uncertain and incomplete data that might soon be available will require new paradigms of in-vehicle knowledge acquisition, reasoning, and data management. For manufacturers, this is of particular importance with respect to the in-vehicle architecture, development process, and lifecycle management. Additionally, for cost effectiveness, the communication systems must not only support driver assistance and active safety but also offer comfort and convenience—hardly an easy undertaking. P



Timo Kosch is a project manager at BMW Group Research and Technology and the coordinator for the European project CoMe-Safety, cofinanced by the European Commission. His research interests include vehicle communications, adaptive systems, and active safety. He received his PhD from the Munich University of Technology. He's a member of the Technical Committee of the Car 2 Car Communication Consortium and leads its system architecture working group. Contact him at timo.kosch@bmw.de.

Markus Strassberger is a researcher at BMW Group Research and Technology and a PhD candidate at the Mobile and Distributed Systems Group at Ludwig-Maximilian-University Munich. He received his Diploma degree in computer science from the Munich University of Technology. He's a member of the Car 2 Car Communication Consortium and is active in the European PReVENT WILLWARN research program. Contact him at markus.strassberger@bmw.de

PERVASIVE VEHICULAR NETWORKS FOR SAFETY

Ken Laberteaux, Lorenzo Caminiti, Derek Caveney, and Hideki Hada,
Toyota Technical Center

Toyota's vision of intelligent transportation systems is as follows: "ITS will satisfy a broad range of societal needs and, when it becomes widely accepted and well-established, cars will also become an important component of the ubiquitous network society of the future" (see www.toyota.co.jp/en/tech/its/mobility). Given a vehicular system with ample computational resources with information sharing provided by wireless communication, many exciting innovations are possible. Here we focus on new technologies that produce advanced safety systems.

On an average day in the US, vehicular collisions kill 116 people and injure 7,900.[1] Governments and automotive companies are responding by making the reduction of vehicular fatalities a top priority.[2,3] In particular, Toyota actively participates in several consortiums that explore safety applications and related technologies (see the "Safety Consortiums" sidebar). In particular, we're working on two promising vehicular-safety applications: the Emergency Brake Warning (EBW) and Intersection Violation Warning (IVW) applications. Here we describe these applications, which we've implemented and demonstrated at the Toyota Technical Center in Ann Arbor,

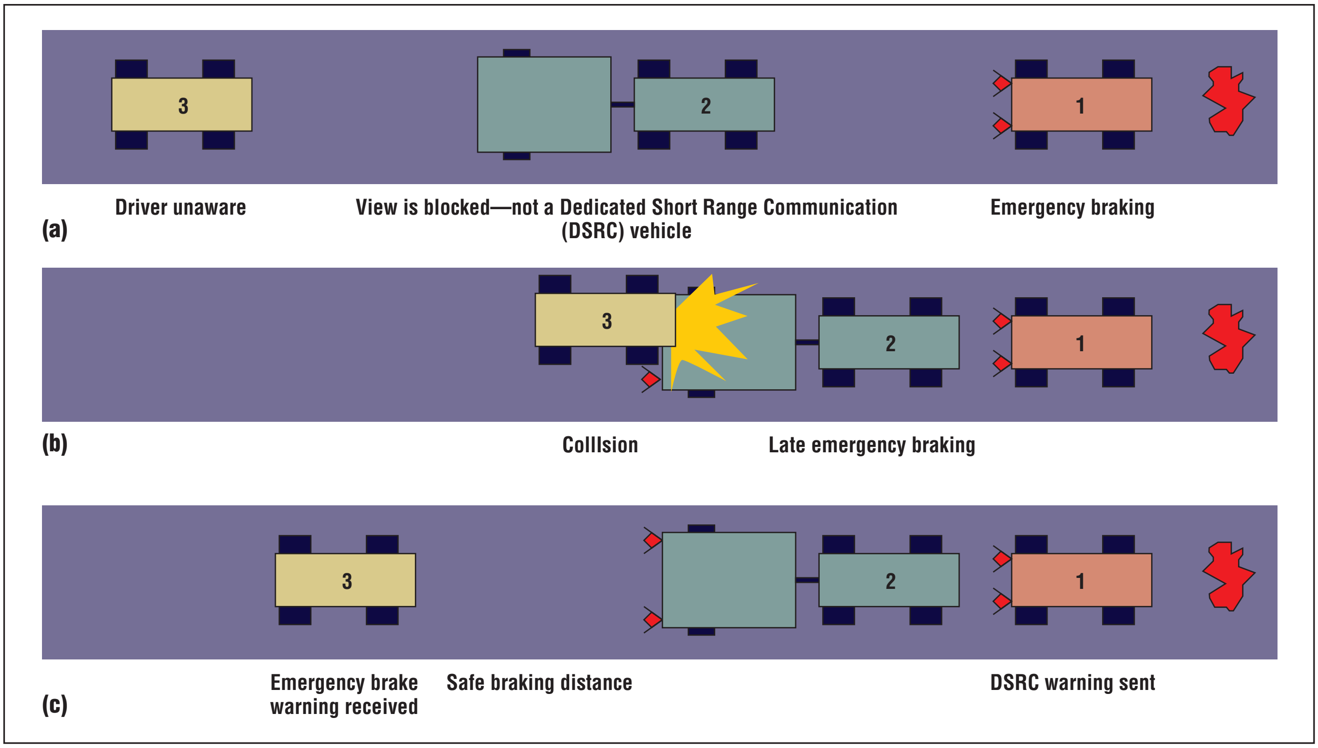


Figure 2. The Emergency Braking Warning application: (a) a braking situation in which one vehicle can't see another vehicle's brake lights—for example, because a larger vehicle is between the two; (b) the resulting collision without an EBW application; (c) EBW provides a brake warning using wireless communication to notify the unaware driver of the unanticipated braking vehicle.

MI, using two Toyota Prius cars. (The task of specifying safety message composition and creation, which a *message dispatcher* handles, is described elsewhere.[4])

SAFETY CONSORTIUMS

Crash Avoidance Metrics Partnership: www-nrd.nhtsa.dot.gov/departments/nrd-12/pubs_rev.html (CAMP comprises BMW, DaimlerChrysler, Ford, GM, Honda, Nissan, Toyota, and Volkswagen and works with the National Highway Traffic Safety Administration)

The Cooperative Intersection Collision Avoidance consortium: www.its.dot.gov/cicas/index.htm

The Advanced Safety Vehicle Project: www.mlit.go.jp (The ASV is a partnership between Japan's 14 automobile, truck, and motorcycle manufactures, sponsored by the Japanese Ministry of Land, Infrastructure and Transport.)

Emergency Brake Warning

The EBW application alerts the driver when a preceding vehicle performs a severe braking maneuver, as figure 2 shows. The application operates by augmenting the brake-light notification system (the rear tail lights in most vehicles) with a system that uses Dedicated Short Range Communication. When vehicle 1 brakes sharply, it transmits a message, indicating that it's undergoing emergency braking. Surrounding vehicles that receive the message must then discern if the event is relevant, because they might receive warnings from vehicles traveling behind, far ahead, or in the opposite direction of them.

More specifically, each vehicle running EBW broadcasts a *heart-beat message* at 3 Hz. Each HBM contains the vehicle's current position, speed, direction, acceleration, and brake-applied status. Each HBM represents these values with short, minimally precise representations, which minimizes channel loading. A vehicle (say, vehicle 1, or the EBW sender) that is braking above a deceleration threshold sends an EBW message at 5 Hz. The EBW message includes a path history (in the form of bread crumbs) over the past several seconds. Furthermore, the EBW contains higher-precision versions of the data elements contained in the HBM. A vehicle that receives the EBW message (such as vehicle 3, or the EBW receiver) must determine if the sender is "relevant" and only warn its driver if the EBW sender lies in the forward path of the EBW receiver (using a proprietary algorithm that uses the bread crumbs of the EBW sender).

Intersection Violation Warning

With the IVW application, a roadside unit, colocated at a traffic-light

SPOTLIGHT

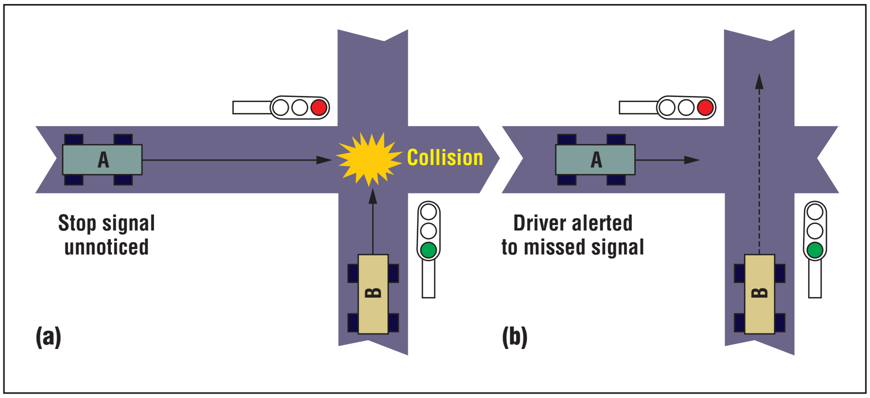


Figure 3. (a) Without Intersection Violation Warning, vehicle A runs the light and collides with vehicle B. (b) When IVW is activated, both drivers are alerted, allowing vehicle A to stop and vehicle B to proceed cautiously through the intersection.

intersection, will broadcast 3Hz information regarding the traffic light, including its location, light status, time until color change, intersection dimensions, and so forth. A vehicle (such as vehicle A) approaching the intersection will use its state to predict a 4-second trajectory. Vehicle A compares its predicted trajectory to determine if it will likely be in the intersection during a red light. If so, the driver of the potentially violating vehicle is alerted. In addition, the violating vehicle broadcasts a message with its speed, direction, and so forth, indicating the likely violation. Recipients of this warning message—for example, the traffic light and surrounding vehicles—can then use this warning notification to take appropriate countermeasures (see figure 3).

Challenges

The two applications we've described require only road-level (3 to 5 m) accuracy of position measurements. This is currently satisfied using differential GPS with a clear view of the sky. However, long periods of GPS blackout are likely in many driving environments, especially in urban settings. Researchers are developing techniques to withstand GPS blackouts, such as fusing vehicle data (speed, acceleration, steering-wheel angle, and so on) or using terrestrial triangulation techniques, but these approaches aren't yet mature. Furthermore, lane-level (1 to 3 m) or sublane (less than 1 m) accuracy would be necessary to perform vehicle-to-vehicle collision warnings and other attractive safety applications.

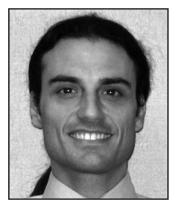
Human-machine interfaces pose yet another challenge. If not well presented to a driver, additional safety information could overload or distract the driver, potentially creating a less-safe condition. Other nonsafety applications, if not well designed and executed, also have the potential to dangerously distract the driver.

These two safety applications, as well as others under consideration, demonstrate the potential of pervasive information in reducing vehicle collisions. It appears likely that the automotive environment can be an early adopter of pervasive computing.

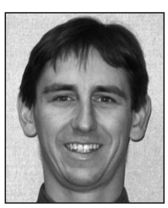
REFERENCES

1. "Traffic Safety Facts," US Nat'l Highway Traffic Safety Administration, tech. report DOT HS 809 767, 2003; www.nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSF2003/809767.pdf.
2. "U.S. Transportation Secretary Mineta Announces Opening of Crash Preventing 'Intelligent Intersection' Test Facility," US Dept. of Transportation, 24 June 2003; www.its.dot.gov/press/fhw2003.htm.
3. "Toyota Safety: Toward Realizing Zero Fatalities and Accidents," Toyota, 2004; www.toyota.co.jp/en/safety_presen/index.html.
4. C. Robinson et al., "Efficient Coordination and Transmission of Data for Cooperative Vehicular Safety Applications," *Proc. Vehicular Ad Hoc Networks 2006*, Sheridan Publishing, 2006, pp. 10–19.

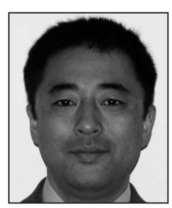
Ken Laberteaux is a senior principal research scientist at the Toyota Technical Center in Ann Arbor, MI. His research interest is the intersection of Control Theory, Communications, and Automotive Safety. He received his PhD in electrical engineering from the University of Notre Dame. Contact him at ken.laberteaux@tema.toyota.com.



Lorenzo Caminiti is a research engineer at the Toyota Technical Center. His current research interests include the creation and validation of advanced vehicular safety applications. He received is masters in engineering from the University of Rome. Contact him at lorenzo.caminiti@tema.toyota.com.



Derek Caveney is a research scientist at the Toyota Technical Center. His research interests include distributed estimation and control for cooperative vehicular safety. He received his PhD in mechanical engineering from the University of California, Berkeley. He's a member of the IEEE and the Society of Automotive Engineers. Contact him at derek.caveney@tema.toyota.com.



Hideki Hada is a manager at the Toyota Technical Center. His focus is on technology planning for intelligent transportation systems and active safety systems. He received an MSE from The Catholic University of America. Contact him at hideki.hada@tema.toyota.com.