Cellular V2X – Hybridization of Long and Short Range Capabilities (1)

Robert A. Gee 1)

1) Continental
1-1-32 Shin-Urashimacho, Kanagawa-ku, Yokohama-shi, Kanagawa-ken, 221-0031, Japan
(E-mail: Robert.Gee@continental-corporation.com)

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ABSTRACT: Cellular V2X, initially defined under 3GPP Rel 14, establishes a baseline of direct device to device connectivity over cellular networks. Whereas traditional use cases may be enhanced with extended warning times, in fact a hybrid long range and short range approach requires further management of message timing and position tracking, combining differing latencies and multiple sensors into a seamless environmental view. Furthermore, the distances feasible in the presence of cellular infrastructure change the use cases, allowing for new far to near transitional cases, and providing impetus for a more integrated HMI combining information, warning, and safety messages.

KEY WORDS: information, communication, and control, inter-vehicle communication/vehicle-to-vehicle communication [E2]

1. Introduction

Over the past two decades, driving related vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communications have generally been based on radio communications with a range of several hundred meters. The evolution of recent communications technologies, in particular Cellular V2X (also known as C-V2X and LTE-V2X) and 4G/5G cellular systems, provide additional capabilities and options to network vehicles with other vehicles, vehicles with local infrastructure (V2I) and vulnerable road users (V2VRU or V2P, meaning pedestrians), and vehicles with systems further afield (Vehicle-to-Network, or V2N).

Most discussions incorporating these additional mid-range and long-range capabilities have focused on basic combinations of traditional long-range V2N use cases such as Hazard Warnings, with short range V2V use cases such as Forward Collision Warning (FCW). These approaches provide the first step in seeking the best of both worlds when combining line of sight communications with long range cellular capabilities. However, the human perspective of driving is not a matter of categorization into “Type: Long” and “Type: Short” use cases, but is instead a continuum of stimuli and reactions, requiring the appropriate driver engagement throughout.

It is not the purpose of this paper to consider which technology should be used for short range communications, such as DSRC or C-V2X PC5. Rather, when combining any short range communications mechanism with longer range connectivity, this paper explores the potential changes that may occur to the overall end-to-end use cases in ways that neither the short range nor the long range use cases originally conceived.

It is also likely that those “Intermediate Range” effects are not singular as well, and may lend themselves to more granular analysis over the intermediate range, particularly because of the rich human-machine interaction possible with the multiple devices in the vehicle. Furthermore, as with any human factors interaction, we must separately consider the interaction of stimulus-response with the human operator as well as the stimulus-automated response possible with computer control of the actuators in modern vehicles.
It is through these analyses that we begin to define a new way of considering long range to short range use cases in order to better identify potential improvements in the human driving experience, maximize safety and efficiency, and spark further discussions to fully leverage the new and enhanced capabilities of these additional communications technologies.

2. The Matter of Constraints

The intent of this paper is to help spur new ways of thinking about driving use cases that in the near future need no longer be constrained by transceiver range, Line-of-Sight (LOS) versus Non-Line-of-Sight (NLOS), data volumes, data throughput, and latencies. While it might at first seem that the exclusion of these considerations grants too broad of a prospective solution set, one need only consider that production use cases do not currently approach the technological limitations of the available communications technologies. In fact, most production vehicles with Telematics communications systems today have average data rates of 20 kbps or less while the vehicles are in use, based on the prevalence of Machine-to-Machine (M2M) or similar data plans with fleet averaged vehicle data limitations from tens to hundreds of megabytes per month, and based on average driving times (2).

On the other hand, it has been true that the current presumptions of specific communications technologies do constrain the definition of the use cases – for example, short range, low latency vehicle-to-vehicle (V2V) use cases have been defined within a range of several hundred meters, and long range use cases have been defined to tolerate terrestrial network and Internet latencies in the range of hundreds of milliseconds to seconds – and the changes to these original assumptions become the basis for the further exploration of the well-known use cases.

Despite that, it remains important to recognize that resources are never unlimited, and no perpetual motion machine can be assumed. This means that gigabit or even hundreds of megabits per second speeds will not be assumed to be available to all vehicles simultaneously or even consistently, and that channel resources are not unlimited. It also means that latency times will vary, and due to a number of factors, many of which are external and cannot be controlled, latencies may often be large or communications may be temporarily unavailable. More subtly, though, it means that there remains a motivation to use communications resources wisely, so that, for example, backhaul capacity differences and potential costs between network providers and across regions do not invalidate the updated use cases.

It is also intended that the business concept of licensed versus unlicensed frequency spectrum is not considered, as the addition would extend the scope into a longer discussion that would not fit into this paper. Such consideration would be more suitable to an overall topic focusing on the communications options which may include discussions of hybrid communications approaches such as the inclusion of low power wide area networks (LP-WAN), satellite, portable transceivers such as smart phones, and other embedded transceivers such as those for remote keyless entry or tire pressure monitoring, the inclusion of any of which may provide further interesting variations to the use cases.

3. Established Information

Where use cases are used as examples in this paper, the focus is on the analysis of the example as the range is extended rather than in the detailed definition of the use case as is being done by multiple organizations. There is ongoing work to further define use cases in automotive consortia at this time, and the ideas from this paper are meant to be additive to those activities.

Likewise, the performance characteristics of the communications technologies are only roughly stated, as these are only pertinent to the use case analysis to the extent that they allow for combination of the technologies into a generally continuous communications experience from long range to short range. In fact, it is the evolving performance for long range technologies such as 4G and 5G cellular that sparked this change: in the past, there were large differences in performance between short range and long range communications, such as latency differences that might be in the range of two orders of magnitude or higher. However, as the evolution of 4G cellular continues to improve network capabilities and 5G cellular has a goal of low single digit millisecond latencies, and if we assume that Internet delays and remote server processing times have potential solutions such as Mobile Edge Computing (MEC), then the long range and short range communications performance differences for many use cases will be so minor as to allow for a reasonably smooth transition from long range to short range communications. Of course, very high performance point to point and point to multipoint communications, such as real time vehicle sensor sharing of 4K or 8K video streams, still present challenges.

Prior research (3) regarding human engagement and reaction times is key to the use cases, and will be important to understand the selection of intermediate range stimuli and potential actions.

4. Humans Versus Machines

In order to define what is meant by Intermediate Range, we approach the question from three directions.

First, we consider typical approaches for driver human machine interfaces (HMI). When the risk is determined by a vehicle that a situation may occur, a driver may receive warnings in the form of audible, visual, or haptic stimuli. And when an undesired situation is determined by the vehicle to be imminent by its sensors (which may include cameras, radar, LiDAR, and V2X communications), a modern vehicle may use its actuators (which may include longitudinal control via accelerators or brakes, or lateral control via steering or selective wheel braking) to slow,

Fig. 3 SAE Driving Automation Levels

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steer, or stop itself, for example by automatic emergency braking (AEB). This means the typical approach by vehicles would be either to provide warnings for which the human should react, or else to provide automated functions such as AEB if it is estimated that the human may not react in time. The decision point between human and computer action becomes particularly critical as vehicles progress to higher levels of automation as per the Society of Automotive Engineers (SAE) definitions in Figure 3, because driver reengagement becomes more difficult over increasing levels of vehicle driving automation as illustrated in Figure 4.

Second, we consider limiting factors of typical short and long range communications technologies. Using this approach, we could define short communications range as approximately 300 meters with long range communications addressing anything beyond. However, while this works for a simple merger of two communications technologies, the principle of distance distinction does not address the complete picture primarily due to human factors.

Therefore, we thirdly consider human factors. Per Table 1, assuming a typical dry roadway that is in good condition but has been in use for some time, 300 meters distance to a hazard point represents a set of available reaction times before strong braking must begin, with a range from 20.6 seconds at 50 kph to 1.3 seconds at 200 kph.

Table 1 300 Meter Dry Roadway Reaction Times (4, 5, 6)

| Dry Roadway          | 50 kph | 100 kph | 200 kph |
|----------------------|--------|---------|---------|
| 300m Travel Time     | 21.6   | 10.8    | 5.4     |
| (seconds)            |        |         |         |
| Braking Distance     | 14     | 56      | 225     |
| (meters), $\mu = 0.7$|        |         |         |
| Available Reaction   | 286    | 244     | 75      |
| Distance (meters)    |        |         |         |
| Available Reaction   | 20.6   | 8.8     | 1.3     |
| Time (seconds)       |        |         |         |

On a wet roadway, these reaction times are reduced to 19.8 seconds and -1.7 seconds (no time to react), respectively.

While at first glance, it would seem these required reaction times for most situations are in the range of human capability, which they mostly are for nominal calculations which estimate reaction times in the range of 1.5 seconds (7).

We also know that typical human reaction times can be much longer under differing initial conditions and dynamic situations. While not suitable for an apples-to-apples direct comparison, what this means is that while 1.5 seconds may be considered nominal by some accident reconstruction specialists, much longer times may occur (8, 9) and may need to be accounted for. These numbers also do not take into account that at night, about one in twelve drivers may be intoxicated (10).

Finally, the reaction times and efficacy of human driving responses are not likely to improve over the coming years. The vast majority of today’s drivers have the advantage of spending 100% of the time in the car practicing and performing the art and skill of driving, and thus benefiting from the mental effect of automaticity (11) in which minor tasks can be performed with little thought. In the future, as automated vehicles become more prevalent, drivers will spend a decreasing percentage of their time in the vehicles engaged in the driving tasks, and perhaps need to engage in driving only every 5,000 miles or more (which equates to about twice per year) as already seen in prototype vehicle data in 2016 and 2017 (12). In short, drivers will fall out of practice.

From this information, at 300 meters and under some circumstances, humans may barely react in time or be too slow. Furthermore, in a two vehicle incident, if either driver has slower than required reaction times, is distracted, is impaired, or is not sufficiently skilled at the driving task, then the accident may still occur. This multiple vehicle, multiple driver consideration only becomes magnified when there are additional human drivers involved in any single incident, leading to the fact that according to one report, 26% of all fatal accidents on weekends are found to involve drunk drivers, and 34% on weekend nights (13).

Therefore, for the purposes of this paper, we consider a simple distance measurement to be insufficient for the definition of short range, as 300 meters is sometimes already in the range of suitability for assisted driving functions in which drivers may require some level of supporting action from the vehicle systems. To bring the range into more human terms, we will set this boundary to approximately 2 seconds (rounding up from the 1.5 seconds as measured by the referenced studies (7)) as that may provide suitable time for most attentive and unimpaired drivers to

Table 2 300 Meter Wet Roadway Reaction Times (6)

| Wet Roadway          | 50 kph | 100 kph | 200 kph |
|----------------------|--------|---------|---------|
| 300m Travel Time     | 21.6   | 10.8    | 5.4     |
| (seconds)            |        |         |         |
| Braking Distance     | 24.6   | 98      | 394     |
| (meters), $\mu = 0.4$|        |         |         |
| Available Reaction   | 275    | 202     | -94     |
| Distance (meters)    |        |         |         |
| Available Reaction   | 19.8   | 7.3     | -1.7    |
| Time (seconds)       |        |         |         |
react. Pertinent to this discussion, we can now define an intermediate range starting at around 2 seconds.

In the past, assisting functions, such as emergency brake assist, might be triggered by the vehicle detecting a panic braking situation based on the movement of a person’s foot on the brake pedal and triggering full vehicle braking, but this tends to occur only at the last moment and when impact is imminent. With the advent of both longer range V2X data and on-board sensor data, the vehicle may have the capability to detect this situation before human reaction begins, and to provide a staged response of assisted driving functions before assuming full autonomous control to mitigate or avoid a collision.

We have now defined the stages, from long range to short range, to include warnings, followed by assisted driving functions, and finally by a computer controlled automated response. The intermediate range should be defined to be relatively long, enabling the vehicle to account for a wide range of human and other conditions, and providing opportunity for a richer set of HMI elements with the driver.

The question then becomes whether a single intermediate stage approach for the assisted driving functions is sufficient. As noted above, humans do not perceive in engineering-defined stages, but rather are immersed in their environment with a continuum of stimuli and responses.

To answer that question, we consider the factors to address when merging long and short range along with human versus computer control. Table 3 lists some factors and related considerations to help define the stages within and beyond the intermediate range.

Table 3 Factors and Considerations for Stages

| Maintaining Primary Task Focus |
|--------------------------------|
| Notifications and Cautionary Warnings |
| Priming |
| Automaticity |
| Experience and Skill |
| Human Reaction Time Limitations |
| Machine Reaction Capabilities |

5. Smoothing the Transitions

When we consider human reaction times, the range of which vary temporally and are generally beyond the capability of the computers to constrain, we recognize that continuous engagement of the driver is the first and perhaps most important factor, lest the driver ignore vehicle warnings to maintain engagement. This stage will be an ongoing challenge as vehicles become ever more automated and drivers tend toward primary task reversal (14), meaning that the primary cognitive task becomes something other than maintaining control and ensuring the safety of the vehicle and its passengers. As some data indicates that when resuming control from an automated driving situation, 15 seconds may be required for the driver to resume control of the vehicle and up to 40 seconds to stabilize vehicle control (8), for the purpose of this paper we will relegate times longer than 40 seconds to the long range warning stage, within which occasional information and cautionary warnings must be coordinated to continue to remind the driver of their responsibility.

To be clear, while the exact times defining the boundaries from short to intermediate, and intermediate to long, are not critical for the discussion in this paper, it is nevertheless relevant to identify the approximate time available to perform the assisted driving functions.

If the driver performs the appropriate actions within the long range, such as changing to an alternative route to avoid the potential situation, then at most the vehicle might provide further notification information but would not need to transition to assisted driving or automated driving stages.

Assuming that the driver does not independently take action and thus moves into the intermediate range, we consider heightened reengagement activities. This is beyond normal driving and thus is the first stage of assisted driving. The reengagement may include priming (15), which means the vehicle systems will gradually prepare the driver to perform the necessary steps, such as to be ready to lift their foot off the accelerator pedal or their hands to steer when necessary. In a way, this is akin to a runner as they assume their “Ready-Set” stance just before a foot race begins, but is different in that the vehicle cannot rely on the driver doing this for themselves. This first stage in the intermediate range of assisted driving focuses less on human direct action and more on preparing the human to perform the potentially needed action. For this, the vehicle system might provide a visual symbol for an upcoming hazard, along with a countdown bar and distance, or might audibly state, “Prepare to brake soon.”

After the priming stage comes the gentle trigger to prompt the driver to take action if the driver has not already done so. In this stage, the vehicle can leverage the concept of automaticity, meaning that it can use techniques that will cause the driver to automatically start to move, like a shoulder tap would likely cause a person to turn their head to see who is touching their shoulder. Vibrations to the steering wheel, audible and haptic indicators to make a person feel as if their tires are hitting the reflective markers on the edge of a lane, or vibrations on the bottom of a foot from an accelerator force feedback pedal (AFFP) can all cause a person to move instinctively. Properly designed, the trigger can help to start the appropriate movement in the right direction. Furthermore, doing this within the intermediate range with many seconds to spare allows for more leisurely action to be taken rather than a high adrenaline, close quarters maneuver.

The third stage of escalation in the intermediate range, providing guided action, is the stage immediately prior to automated control by the vehicle. In contrast with priming and triggers which prompt the beginning of human action, guided action means the vehicle may guide the driver through a larger portion of the necessary action, and may help to remind the driver to correct an invalid mental model of the vehicle’s capabilities,
perhaps due to lack of experience or driving skill. For example, this may mean a steering wheel may apply some force in one direction to guide the driver to avoid a hazard in the other direction, or an AFFP, instead of vibrating, may push back on the driver’s foot to strongly encourage them to take their foot off the pedal. This final intermediate stage physically guides the driver to implement the appropriate action, and by doing so can also help to improve the safety margin of the final automated maneuver, for example by incrementally slowing the vehicle before automatic emergency braking begins. It is at this stage that immediate human action is required, and if not undertaken in a timely and sufficient manner, then it may be that the only predictable solution would involve machine intervention due to the inexact lower limit of driver reaction times.

Finally, if the driver still has not taken adequate action, short range automated solutions may begin in which the humans might only be observers of the automated driving functions.

This leads to the staged model as shown in Figure 5.

6. Emergency Vehicle Approaching

To illustrate this approach, we start with a simple two vehicle use case including an emergency vehicle. Using long range C-V2X capabilities, a vehicle becomes aware that an emergency vehicle is in the area, and calculates that the vehicle will be within a predefined range and direction such that the driver should be notified.

While still within the long range category as defined in this paper, the vehicle provides an information notification to the driver. The driver is now apprised of the situation and may choose to actively listen for the siren or to watch for flashing lights and other nearby traffic behavior. If the driver or the emergency vehicle then turns away and interception seems unlikely, after a suitable hysteresis margin the vehicle may provide a visual indicator or chime that simply conveys that the emergency vehicle is now out of range.

If the driver continues to approach the emergency vehicle, and at the upper bound of the defined intermediate range, the vehicle may provide more detailed information, such as an easily understandable warning symbol, a distance countdown bar, and the calculated distance in feet or meters.

Continuing closer, and at the upper range at which the driver should consider modifying the vehicle speed, the vehicle’s AFFP begins to vibrate, with a common result that the driver will decrease their foot pressure on the accelerator and begin to slow the vehicle.

Finally, as the vehicle determines the driver must slow much more rapidly, it can cause the AFFP to push back on the driver’s foot, guiding them to remove their foot completely from the accelerator and more strongly suggesting a braking maneuver.

At the last moment, of course, if a collision becomes imminent and it becomes possible that the driver may not react in time, the vehicle performs an emergency brake assist maneuver to avoid the collision.

7. Preview ESC

As another use case example, Preview ESC (Electronic Stability Control), is a single vehicle function that can be implemented either standalone, with long range V2N, or with V2I. Preview ESC differs from traditional ESC in that it anticipates potential loss of control scenarios and can take action before slippage occurs.

It uses eHorizon (16) (Electronic Horizon) data, which is map data that is tailored and focused not for navigation, but for driving. This data, for example, can allow a vehicle to know the curvature, slope, and speed for upcoming road segments. The standalone (or static) version stores this eHorizon data on the vehicle itself, such that no network connection is necessary, but when combined with V2N or V2I connectivity, it may also include dynamic data such as reports of hazardous weather conditions about ice on the road ahead. This could allow a vehicle to know a nominal or average speed when driving around a curve, and also when such a nominal speed may yet be unsafe due to detection of a lower friction coefficient by vehicles or other mechanisms sensing the road in the distance.

Without such a Preview ESC function, a driver would be left to their own estimations of what a safe driving speed would be, and if they guess it incorrectly, the normal ESC function would engage when the vehicle detects slippage. While the performance of modern ESC functions may be quite good, it should be a foregone conclusion that entering a curve below the maximum safe speed, relative to the prevailing environmental conditions, and thus avoiding any slippage between the tires and the road surface, is a much preferable situation than relying on ESC to minimize slippage after it begins. For this, we follow the same method as outlined in this paper.

Within the long range, the driver may receive an on screen notification that slippery conditions exist ahead, or even if under ideal road conditions, that the vehicle is approaching a curve with a recommended speed lower than the current vehicle speed.

Entering the intermediate range, the vehicle may provide a simple icon indicating the hazard, a distance countdown bar, and the numerical distance.

The AFFP again begins to vibrate, or the steering wheel to vibrate, prompting the driver to take action.

With some seconds before the curve, the vehicle begins to bleed off speed by pushing the AFFP back more forcefully.

Finally, with only seconds before entering the curve, and if the vehicle speed is deemed to be dangerously high, the vehicle may opt to take autonomous action, directly applying the brakes.
to slow the vehicle and enter the curve with a more reasonable speed. Note that all of these actions, including the autonomous final action, have occurred before the vehicle enters the curve, thus minimizing the likelihood of actual ESC activation.

This type of use case, with preemptive action that occurs before the vehicle is on the verge of losing control and avoiding even the reduction of control, often begs the question of what the consumer would accept, and whether a driver would prefer to maintain complete control despite the risks. The answer is simple and threefold.

First, regional legislation sometimes dictates the function. For example, airbags are required in the United States, while across Europe there is no overall law for airbags; conversely, Europe requires pedestrian protection of the type that the United States does not.

Second, when not required by legislation, automobile manufacturers can tune the use cases for branding and consumer desires, akin to tuning of the engine and transmission for comfort or performance.

Finally, the approach described in this paper does not dictate the specific HMI and actions for assisted driving, and the options will vary based on vehicle equipment.

8. Smart Cities, Smart Roads

Intelligent transportation systems (ITS) have been gradually deployed over the past decades. V2X, and especially that which is enabled by both short and long range communications, increase the number of possibilities for ITS and the potential to reduce congestion and emissions.

Take for example platooning. The benefits of closely-spaced vehicles moving as a coordinated pack are well known, reducing wind resistance and improving fuel efficiency for every vehicle in the platoon. The risks of vehicles that would otherwise be considered as tailgating if under the sole control of human drivers are alleviated by V2V communications, allowing all vehicles to accelerate and decelerate nearly as one. As defined in this paper, the intermediate range of assisted driving has borders not delineated by distance, but rather by time, and we can further interpret this as time to an event rather than simply stopping or swerving to avoid a collision.

Applying this to platooning, consider as well that many such convoys will travel on multi-lane highways. With controlled entry and exit ramps on the outside edge of the road, the innermost lanes are considered the “passing” or “fast” lanes and may be used by vehicles travelling longer distances, thus reducing for long distance travelers the small perturbations as vehicles enter and exit the highway. Writer Robert Heinlein, in his prescient 1940 story “The Roads Must Roll” (17) that was written before superhighways became popular in the United States, envisioned a “Road” in which each inner lane moved more quickly than the next one closer to the outer edge. Future smart roads with V2X may do the same: vehicles platooning and travelling the longest distances would be moved to the innermost and fastest lanes. As they begin to approach their exit point, the vehicle would reengage the driver and support them to slowly and eventually change lanes toward the outer edge of the roadway over a period of time, until finally the vehicle was in the outermost lane before reaching its exit.

For smart cities, similar principles could be applied to swarms of vehicles as they traverse surface roads with at-grade intersections, meaning intersections that require traffic from one direction to stop or yield while traffic from another direction proceeds. Similar to highway platoons, intermediate stage functions could include individual lane guidance for each vehicle, positioning each vehicle for an upcoming left or right turn, or optimizing the traffic flow by grouping vehicles into single lane streams that minimize the overall number of lane changes. Keeping city vehicles on the “straight and narrow,” minimizing traffic-slowing lane change perturbations with their corresponding affects on vehicle queues, and thereby reducing the opportunities for accidents and reducing emissions, creates a set of ITS possibilities and enables municipal traffic management centers to optimize by region what individual vehicles might never detect using only short range communications.

9. Conclusion

In this paper, we have discussed the current focus on communications for long range and short range vehicular use cases, and have presented considerations that would affect why and how we should implement an intermediate range. Because of these considerations, we defined the intermediate range based on the guidance from human factors and identified three stages within the intermediate range. These stages provide the additional benefit of providing a smoother, more comprehensible flow from long range information to short range autonomous action, while allowing every opportunity for the human driver to select and enable their own choice for action.

Furthermore, this approach does not restrict the specific solution, but rather provides guidance for implementation while allowing differentiation subject to branding desires, consumer interests, and regional legislation.

While there is much advertisement for the improved specifications of the latest communications technologies, it may be in the use of these technologies, for the further humanization of the use cases as perceived by the drivers, that we finally start to
bridge the ever-widening gap between technological capabilities and human evolutionary limitations, leading to safer, more efficient, and more comfortable transportation from Point A to Point B.

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