Connected Vehicles: Cognition Saves Lives

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***Abstract*—The idea of autonomous cars and connected vehicles is becoming increasingly pervasive in research labs and car manufacturing companies. It is inevitable that roads are going to accommodate autonomous and semi-autonomous vehicles in the near future. However, like other technologies filtering into humans daily life, the transition from conventional transportation systems to autonomous vehicles requires careful involvement of human-oriented factors into related technologies. We believe employing cognition in vehicular decision making processes improves the awareness and consequently safety and comfort in the roads. Here, we discuss how affect-driven integration of cognition into connected vehicles can do so.**

***Index terms*—** Cognition, Awareness, Connected Vehicles.

I. Become Connected, Become Aware

In February 2014, the National Highway Traffic Safety Administration (NHTSA) announced that Intelligent Transportation Systems (ITS), including connected vehicle technology, will be required in all cars by 2019 [1]. Subsequently, there has been a significant increase in research activities with respect to vehicular networks (VANETs) in respond to this urgent need to address vehicular traffic safety concerns [2]. Toyota Group recently announced that it is investing \$50 M to design and produce artificial intelligence within vehicular networks [3]. The information flow within a connected vehicle network, which includes both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), is managed via the broadcasting of control messages over a control channel. In Europe, these messages are referred to as Cooperative Awareness Messages (CAMs) while in the United States they are called Basic Safety Messages (BSMs). Shared information, such as vehicle position, motion characteristics, and vehicle size, are used for increasing the overall environmental awareness in support of *safety applications,* (*e.g.,* intersection movement assist, left turn assist, do not pass warning sign, and light violation warning) as well as *mobility applications,* (*e.g.,* collision warning, road coefficient of friction, road conditions, parking management, and payment solutions) [4].

Figure 1: Our prototype autonomous vehicle.

Semi and fully autonomous vehicles improve traffic safety by preventing human-driver mistakes. Google and Ford are performing one of the mainstream trials of autonomous vehicles while Volvo and Honda are working on increasing vehicles' awareness through providing robust connectivity in vehicular environments. Connected vehicles stand as a breakthrough in intelligent transportation, while introducing some technological challenges. In order to enable robust and efficient ITS mechanisms, several technical challenges associated with autonomous vehicles must be addressed, including:

- Human-driver errors confront autonomous systems with unexpected situations that make predefined decision mechanisms insufficient,
- Dynamic vehicular environments include obstacles that vary with time, changing number of vehicles, and varying road topology,
- Decision making mechanisms in ITS are not delay-tolerant since the network environment changes rapidly,
- Frequently broadcasting between connected vehicles causes overhead on the processing unit at each vehicle.

One promising feature that is under investigation in autonomous cars is cognition. Cognition enables vehicles to improve driving quality by improving safety of the vehicle's occupants and other vehicles [5]. Moreover, the driver or passenger's thoughts and habits will be linked to decision processes. This feature provides a method to transition from fully human driven to half autonomous and half human driven, and finally to fully autonomous vehicles on roads.

We believe cognition in connected vehicles can:

- reduce the amount of errors on the roads caused by drivers, since autonomous vehicles will not only drive based on more accurate perception, but will also include the behavior models of their neighbors before making any decision,
- reduce the amount of required communication since the autonomous cars only need to transfer high level decisions based on their own sensory information rather than an enormous amount of low level sensory data,
- improve the quality of travelling on the roads in terms of safety and comfort, since cognition increases awareness of each autonomous vehicle on the road.

II. Connected Vehicles and Driving Environments

A. Building Blocks of A Connected Vehicle

Hardware components shape the technical practicality and readiness of ITS solutions [4]. Our proposed cognition framework uses existing components without requiring extra functionality. The intra-vehicle components are categorized in six main blocks as shown in Figure 2. As shown, the internal vehicle components include two DSRC radios, which standardization is still under development. One proposal is to dedicate one radio permanently to safety messages. An alternative proposal is to design a multi-channel hopping algorithm to use the radios adaptively. These radios provide information sharing with other ITS members to increase awareness on the roads.

Another vital component for cognition in vehicles is the Global Positioning System (GPS) receiver for gathering position and timekeeping information. A computer processing unit uses this information with the data generated from onboard sensors such as heading, speed, and acceleration to provide the information to intra- and inter- vehicle intelligence systems. The safety electronic control unit prepares BSMs to periodically broadcast in order to run the safety applications. The memory unit satisfies the needs of the data acquisition system and

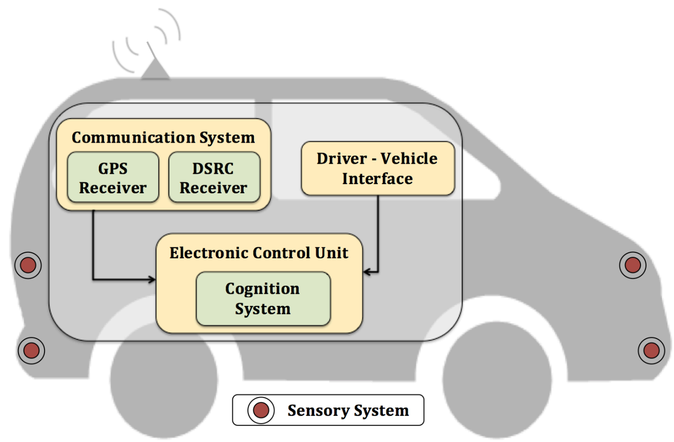


Figure 2: Intra-vehicle components can be used for cognition [4].

records the historical data on the cognition of its own and other vehicles. The memory unit also stores security certificates. Lastly, a driver-vehicle interface would issue warnings to the driver. Such warnings could be audible, visual, or haptic, e.g., any type of audio-visual alarm, tightening of the seat belt, or vibrating the driver's seat.

B. Roads as Social Environments

A social environment contains one's social relationships as well as one's resources and physical surroundings. A social relationship is the most dynamic part of a social environment. Hence, developing and maintaining positive social relationships is crucial for a social environment and is influenced by the individuals' quality of interaction. Roads are social environments in which individual vehicles interact with each other through their "nonverbal" behaviors, each subject to the same traffic laws. However, there are many violations of the laws on roads all over the world on a daily basis which leads to expensive and all-too-often heart-breaking failures. These failures are mostly caused by the failure of drivers to effectively interpret their driving environment and make appropriate decisions with respect to their constraints such as lack of time, lack of perception, and a plethora of cognitive load. Therefore, it is crucial to involve cognition in the vehicles to share the *meaning* of what they perceive rather than broadcasting data coming from their sensory system. For example, any sensory information leading to an alert on a particular vehicle does not necessarily have the same meaning for both the occupants and the neighbors of that vehicle. The alert warns the occupants of the vehicle to be aware of an internal failure (e.g., malfunction in the transmission system), or an external adversary (e.g., an animal unexpectedly leaping into the road). The same alert has a

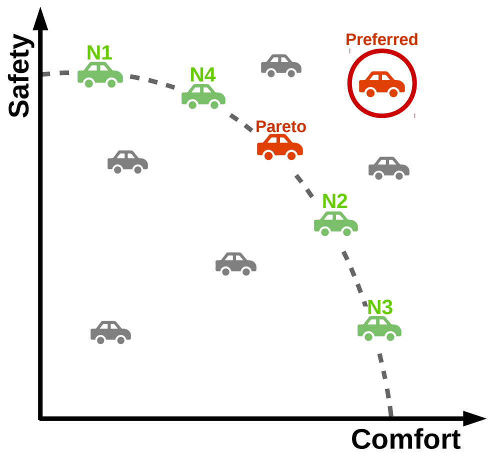


Figure 3: Pareto optimal decisions for the neighbors.

different meaning for a close vehicle approaching from behind; no matter what caused the alert in the leading vehicle, the posterior vehicle should slow down effective immediately. However, the same alert can be interpreted in an entirely different way for a neighbor in front of the originally alerted vehicle. In fact, this vehicle can ignore the received alert and continue a safe drive. Ultimately, these type of improvements leads to a higher quality of vehicles' interaction which consequently increases the safety of the roads.

C. *Driving Needs Pareto Optimal Decisions*

Cognitive architectures are used to solve high-dimensional multi-objective tasks and to make proper decisions with respect to the dynamics of such environments. Most of the time the real world problems possess a high level of complexity due to the dynamism involved in the environment. A social environment is an example of such complex environments. A social environment includes humans as variety of sources making decisions independently but interrelated to each other. Roads are social environments and driving is the social act of drivers' behavior. It is clear that driving involves many decisions in which a driver needs to maintain its own objectives while recognizing objectives of the others.

Let's consider two general objectives, *Safety* and *Comfort*, for any driver while driving between the source and the destination. Indeed, we can expect all drivers would like to maximize both of these objectives. However, while they need to obey the traffic law, they also need to take into account their neighbors' driving behaviors, and respect their objectives. In the example shown in Figure 3, the red car's driver wants to maximize her own safety and comfort to her aspiration level for both objectives to obtain the "preferred" point. We believe at least for a certain radius, the red vehicle should consider objectives of the other vehicles in that neighborhood (four vehicles shown in green), and update their anticipated and its own state based on their behaviors. To achieve this goal, a cognitive system should be able to make decisions such that it is impossible to make the state of self better off without making the state of at least one of the neighbors worse off. Therefore, the cognitive system's decision for any given event should be a pareto optimal solution, since the neighboring connected vehicles' objectives are important for each individual vehicle. Here, we only used the concept of pareto optimality to discuss the type of decisions a cognitive system of a vehicle should make. Our cognition framework and the underlying mechanisms do not take a game theoretic approach to make decision-making.

III. Cognition Systems

Integration of cogniton into connected vehicles needs us to understand the building blocks of cognition, how they relate to each other, and what functional operations they provide. We choose Newell's general theory of cognitive control, PEACTIDM [6], to describe the underlying abstract processes of a cognitive system. PEACTIDM is a theory of cognitive control where cognition is decomposed into a set of eight abstract functional operations [6] all of which are hypothesized as the building blocks of one's immediate behavior. Figure 4 shows the sequence of PEACTIDM's building blocks.

Perceive is the reception of raw sensory data. For instance, connected vehicles receive data from both their own local sensory system (e.g., GPS) and their neighbor vehicles (e.g., an abrupt change in their velocities). *Encode* is the transformation of the sensory data into features that the cognitive system can process. In the cognitive architectures using Bratman's BDI paradigm [7] each sensory data will be tranformed into a new *belief*. The cognitive architecture will be able to use these beliefs in different processes. For example, in connected vehicles there will be a belief about the current acceleration of the vehicle which corresponds to the sensory data indicating this value. *Attend* is the act of shifting or maintaining the focus of attention on an event. For instance, an alert raised because of a sudden speed reduction of multiple leading neighbor vehicles needs to be attended to immediately, while the same alert does not need the same level of attention if the leading vehicles are a few miles apart. *Comprehend* is the act of trnasforming an event into a goal or task-spcific representation and inferring the curent status of the world. For instance, a vehicle receiving an alert requiring an immediate reaction needs to identify the cause of the problem even if the alert was raised and

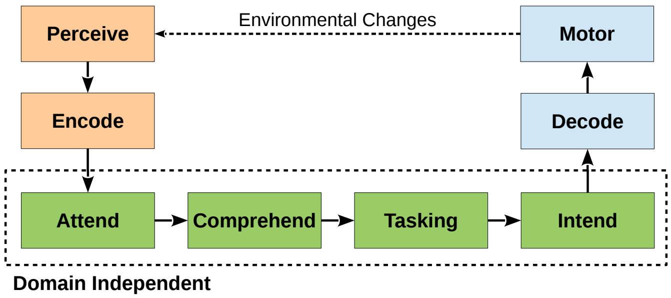


Figure 4: PEACTIDM

received from another vehicle. Thus, the receiver of the alert can apply replanning if necessary.

Tasking is the process of recognizing a goal based on the new state of the world. For example, a vehicle can recognize a goal in the plan to exit the highway with respect to the new beliefs about an accident a few miles ahead and the current state of the highway which includes slow-moving traffic. *Intend* initiates a future action based on the current goal as a response to the current event. For instance, if the current goal of the vehicle is to leave the highway, the vehicle begins to change lanes to the right-most lane to be able to take the next exit. *Decode* translates the response based on the given *intention* into a series of motor actions. For instance, if the intention is changing lanes to the right, the vehicle applies a series of actions including using the right blinker, checking the occupancy status of the right lane, and turning the steering wheel to the right whenever it is appropriate. *Motor* executes the actions decoded based on the given intention. For example, in the case of a lane change, the blinker starts to blink and the wheels turn to the right respective to the amount of change at the steering wheel.

IV. Affective Motivational Collaboration Theory

Affective Motivational Collaboration Theory [8] is about the interpretation and prediction of observable behaviors in a dyadic collaborative interaction. Affective Motivational Collaboration Theory specifies the processes involved in the progress of a collaboration and how they impact the collaboration's underlying structure. This theory is built on the foundations of the *SharedPlans* theory of collaboration [9] and the *cognitive appraisal* theory of emotions [10].

The theory focuses on the processes regulated by emotional states. It aims to explain both rapid emotional reactions to events as well as slower, more deliberative responses. The observable behaviors represent the outcome of reactive and deliberative processes related to the interpretation of the self's relationship to the

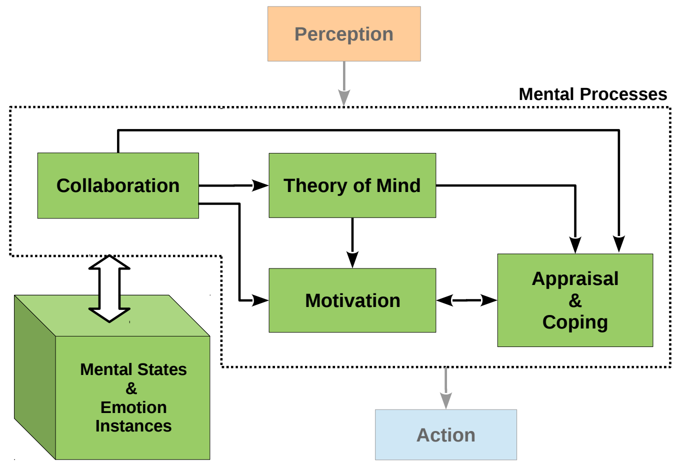


Figure 5: Computational framework based on Affective Motivational Collaboration Theory (arrows indicate primary influences between mechanisms).

collaborative environment. The reactive and deliberative processes are triggered by two types of events: *external* events, such as the other's *nonverbal behaviors* and *primitive actions*, and *internal* events, comprising changes in the self's mental states, such as belief formation and emotional changes.

Affective Motivational Collaboration Theory explains how emotions regulate the underlying processes when these events occur during collaboration. This theory elucidates the role of motives as goal-driven affect-regulated constructs with which an agent can form new intentions to cope with internal and external events. Therefore, a new motive can become a new intention and the self can take a new action based on the new intention. The focus of the underlying mechanisms is on the ones depicted as mental processes in Figure 5 along with the mental states.

The *Mental States* includes ego's (vehicle's) beliefs, intentions, motives, goals and emotion instances as well as the anticipated Mental States of the neighbors (other vehicles). For instance, every sensory data, every threshold value, or every piece of inferred information about the world has a corresponding belief in the Mental States. The *Collaboration* mechanism maintains constraints on actions, including task states and the ordering of tasks. Although maintaining safety and comfort is a goal for each individual vehicle, all vehicles also have a shared goal which is sharing the road with others – at least partially – to get to their destinations. Therefore, vehicles require the collaboration mechanism to maintain their full or partial shared plan. The *Collaboration* mechanism also provides processes to update and monitor the shared plan. The *Appraisal* mechanism is responsible for evaluating changes in the ego's Mental States, the anticipated

Mental States of the neighbors, and the state of the collaboration environment. The outcome of appraisal impacts every vehicle as an evaluative, regulatory, or motivative process. For instance, the *expectedness* of an event indicates how prepared the ego is to cope with the event, or how to maintain the current state with respect to the current changes in neighbors' location. The *Coping* mechanism provides the ego with different coping strategies associated with changes in the ego's mental states with respect to the state of the collaboration. For instance, does ego need to change speed with respect to the current state of the road, or does it need to replan to get to the destination. The *Motivation* mechanism operates whenever the ego a) requires a new motive to form a new intention with respect to the current event, or b) wants to interpret a neighbor's motive whenever the neighbor's behavior triggers an alarm after ego appraises the situation. The *Theory of Mind* mechanism is the mechanism that infers a model of the neighbor's anticipated mental state. The ego progressively updates this model during the collaboration. A neighbor's model impacts ego's decision with respect to the state of the neighbor.

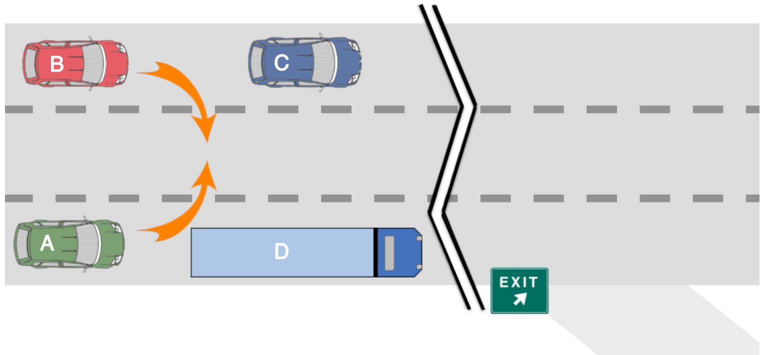
V. Example Scenario

According to analysis of lane changes by the US' National Highway Traffic Safety Administration (NHTSA) in 2003 [11] more than 38% of pre-crash movements in the highways were caused by typical lane changes. Furthermore, according to the NHTSA's traffic safety facts of February 2015 [12], about the 94% of the critical reasons of pre-crash events are attributed to the drivers. As mentioned in this report, about 41% of the driver-related critical reasons are because of the ***drivers' recognition errors*** including drivers' inattention, internal and external distractions, and inadequate surveillance. Also, about 33% of pre-crash reasons are caused by the ***drivers' decision errors*** such as driving too fast for conditions, too fast for the curve, false assumption of others actions, illegal maneuver and misjudgment of gap or others speed. In our hypothetical example, we show how the involvement of different mechanisms in our framework can improve safety and comfort for both the ego vehicle and the other neighbor(s) in the roads for such conditions.

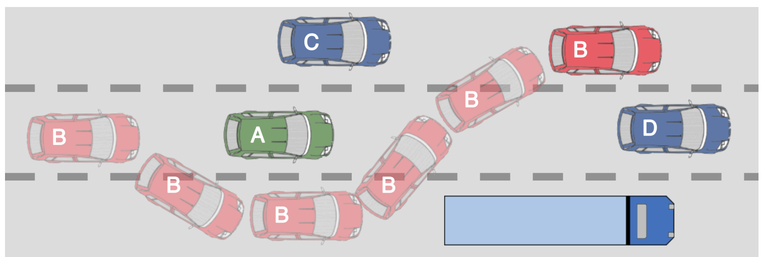
In this example (see Figure 6(a)), autonomous Vehicle *A* (ego vehicle) travelling in the right lane wants to take Exit *x* in two miles. However, the ego vehicle has decided to pass the slow-moving Truck *D* before taking Exit *x*. At the same time, Vehicle *B*, travelling in the left lane, quickly approaches a slower car, Vehicle *C* in the same lane. Vehicle *B*'s driver decides to change lanes to the middle lane to pass Vehicle *C*. Therefore, both the autonomous Vehicle *A* and the driver of Vehicle *B* want to go to the middle lane at the same time; since the middle lane is not occupied by any other vehicle. Hence, because both Vehicle *A* and Vehicle *B* are not aware of each other's intention, they can cause an accident irrespective of the responsibility of each vehicle with respect to the traffic law.

In this example, the ego vehicle perceives a sudden change of lane by Vehicle *B*; then it appraises this event as *relevant, undesirable, unexpected*, and *controllable*. The lane change by Vehicle *B* is relevant to ego vehicle since it decreases the utility of the current goal for the ego vehicle; it is undesirable since the ego vehicle's attempted goal (lane change) is not achieved (i.e., it is blocked); it is unexpected since Vehicle *B* interrupted the ego vehicle's pursuit of its current goal; and it is controllable since the ego vehicle still has three alternative goals. The goal management process in our framework ranks all of the potential goals based on their status in the plan structure, and the outcome of the self and the reverse appraisal. Moreover, in this incident the ego vehicle does not have a behavior model of the Vehicle *B*, since Vehicle *B* has just reached the ego vehicle and is perceived for the first time. Therefore, first, the ego vehicle replaces the current goal with stay-in-the-lane goal for the prupose of recovering from the blocked goal. In general, the ego vehicle adopts one of the safe predefined tactical goals, e.g., stay-in-the-lane or reduce-speed, as an alternative goal to the original goal which would raise unexpected and undesirable events. Next, the ego vehicle chooses the *restraint coping strategy* to immediately pull back into the right lane to yield the the middle lane to Vehicle *B* avoiding any possible accident. Therefore, choosing an appropriate coping strategy, the ego vehicle responds to the current goal change using the sensory system and taking appropriate actions to pursue the new stay-in-the-lane goal. The ego vehicle updates Vehicle *B*'s user model to a reckless driver. As shown in this example, the cognition of the autonomous vehicle prevented an accident which could happen because of the drivers' recognition error caused by their inadequate surveillance of the highway.

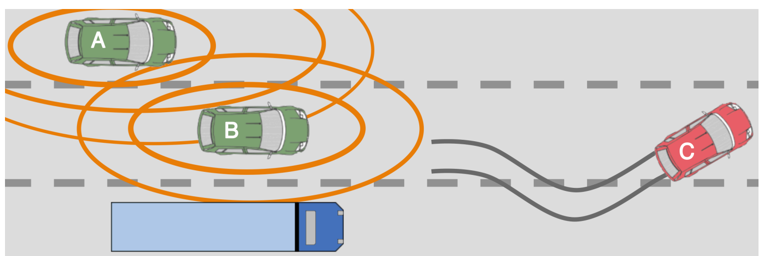
In the next incident (see Figure 6(b)), the ego vehicle perceives Vehicle *B* quickly approaching from behind in the middle lane (event 1). Vehicle *B* changes its lane to the right lane (instead of left) to pass the ego vehicle immediately after reaching the ego vehicle (event 2). As shown in Figure 6(b), Vehicle *B* has to switch back to the middle lane quickly (event 3), since there is a slow-moving truck in the right lane at a short distance ahead of the ego vehicle. However, Vehicle *D* makes another



(a) Being aware of other drivers' intention.



(b) Coping with the driving behavior of a reckless driver.



(c) Communicating the behavior model of careless driver.

Figure 6: Three incidents in our scenario.

blockage for Vehicle *B* in the middle lane. Consequently, Vehicle *B* has to switch to the left lane to pass this blockage (event 4). All these four events happen in a few seconds in the neigborhood of the ego vehicle.

Similar to the first incident, the ego vehicle appraises the first event as highly *relevant, undesirable, unexpected* and *controllable* for the self, and *relevant, desirable* and *expected* with low value of *controllability* for Vehicle *B*. Therefore, the ego Vehicle, creates a behavior model for Vehicle *B* with a high probability of having a *speeding* driver. The next three events will be also appraised in the same way. The ego vehicle updates Vehicle *B*'s behavior model based on each event, raising the probability of Vehicle *B* having a *speeding* driver. Updating Vehicle *B*'s behavior model based on several events leads to a more accurate behavior model of Vehicle *B*. Consequently, the ego vehicle will able be to evaluate Vehicle *B*'s actions more accurately based on the reverse appraisal process. The outcome of the self and reverse appraisal processes causes the goal management process to employ another tactical goal, i.e., reduce-speed. Hence, the ego vehicle as the outcome of the appraisal and the behavior modeling processess adopts *behavioral disengagement* as the most appropriate coping strategy. Furthermore, Vehicle *B*'s behavior model not only helps the ego vehicle to be safe while travelling in its neighborhood, but it can also inform other autonomous vehicles to drive carefully while Vehicle *B* is within a short distance from them.

In the last incident the ego vehicle (Vehicle *A*) simply passes another autonomous car (Vehicle *B*) which is driving in the middle lane with a normal speed (see Figure 6(c)). Vehicle *B* also detects the appearance of another autonomous vehicle in its own neighborhood. The ego vehicle receives an alert from Vehicle *B* regarding the car (Vehicle *C*) travelling a few hundred feet in front of them in the middle lane. The alert message contains a vector

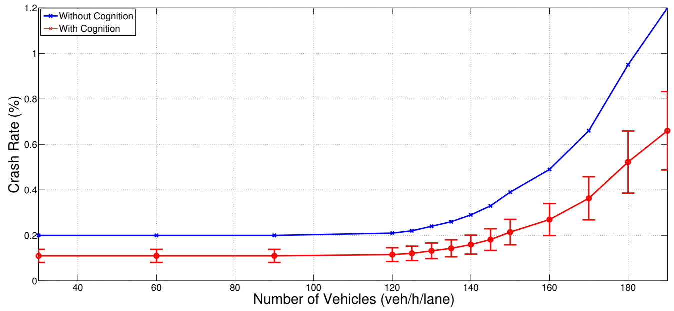


Figure 7: The impact of cognition on reducing the crash rate caused by human error.

of probabilities of Vehicle *C*'s driver type indicating the following probabilities: 34% chance of being *drowsy driver*, 32% of chance of driving *under the influence of drugs or alcohol*, 28% chance of being a *distracted driver*, and 6% chance of being a *teenage driver*. These values are computed by Vehicle *B*'s Bayesian behavior modelling process in the the Theory of Mind mechanism. The comoputation of these probability values is based on Vehicle *B*'s perception and appraisal of the road including Vehicle *C*, even before the ego vehicle reaches to Vehicle *B*. Afterwards, the ego vehicle uses the content of alert message to update it's own behavior model of the Vehicle *C*. Updating Vehicle *C*'s behavior model does not change the ego vehicle's current goal. It also does not demand the ego vehicle to apply an immediate reactive change in its own driving behavior. However, it replaces the current motive (i.e., maintain the current speed) of the ego vehicle with a new motive (i.e., maintain the current distance with Vehicle *C*). Forming this new motive is based on the outcome of the Theory of Mind (updated by another vehicle) and the Appraisal mechanisms. The new motive is urgent since it requires an immediate change in ego vehicle's driving behavior, and it is important since it is related to the current goal that the ego vehicle pursues. Therefore, the new motive causes the ego vehicle to adopt an *active coping strategy* to circumvent the stressor (i.e., Vehicle *C*) by maintaining its distance.

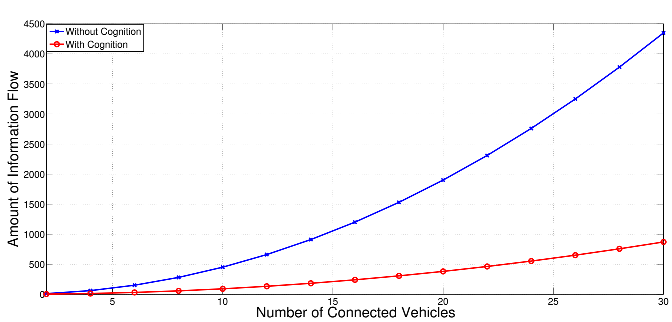


Figure 8: The impact of cognition on the required data transfer rate between connected vehicles.

Recent reports show that traffic density and crash rate is highly correlated. In [13], the relationships between traffic density, speed and crash rate are modeled based on traffic reports from Denver, Colorado. In Figure 7, the crash rate shown in the blue line is based on the data from this report without applying our proposed cognition framework in each vehicle. The proposed cognition framework can reduce the crash rate caused by human errors upto 80%. The red line in this figure indicates a significant influence of using our proposed cognition framework, reducing the crash rate based on the same data.

Furthermore, the proposed cognition framework decreases the amount of information flow due to communicating vehicles' decisions rather than their raw sensory information. Assuming each vehicle has 5 sensors, Figure 8 shows the change in amount of sensory information flow with respect to the size of the connected vehicles' network. In general, for n number of connected vehicles, each vehicle sends 5 sensory information packets to $n-1$ neighbor vehicles. Therefore, the total number of times that the vehicles of the given network exchange their sensory information is $5n(n-1)$. On the other hand, using the proposed cognition framework each vehicle only need to communicate its decisions rather than its raw sensory information. Hence, the number of information packets exchanged for a network of n connected vehicles is $n(n-1)$. As a result, using the proposed cognition framework provides a solution to messaging overhead.

VI. Summary and Research Directions

The human-driven errors need to be considered for a successful transition from conventional to fully autonomous vehicles. The proposed cognition framework promises a solid decision making process to deal with this transition in transportation system. Affective Motivational Collaboration Theory provides fundamental evaluative, motivative, and decision making processes to improve awareness beyond sensory information. The underlying mechanisms facilitate reactive and deliberative decisions with respect to the events in the vehicular environments. Using the proposed cognition framework can reduce human-driven errors, and required amount of information exchange leading to the improvement of safety and comfort for the occupants of the connected vehicles and their neighbors. We will employ our proposed cognition framework in our autonomous vehicle testbed in our future works. We will benchmark the performance of our autonomous vehicle using our cognition framwork in different traffic scenarios.

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