Messages for Cooperative Adaptive Cruise Control Using V2V Communication in Real Traffic

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1. Introduction

Automated vehicle technologies have been implemented in practice progressively for at least a decade in passenger cars and commercial vehicles. A predecessor technology was Cruise Control (CC) which regulates the vehicle speed to the driver desired/selected speed regardless of traffic in its immediate front, so that the driver needs to adjust the set-speed for a proper following distance. The first stage of automation is Adaptive Cruise Control (ACC) which incorporates forward remote sensor detection such as radar/lidar for front target detection, tracking and relative distance/speed estimation. ACC involves both speed and relative distance control. Although ACC advances significantly beyond CC, it still cannot maintain string stability for multiple vehicles in tandem with short enough following distance, i.e. if 3 or more vehicle in tandem are in ACC mode and if the leader vehicle speed fluctuates due to traffic ahead, this fluctuation will be amplified towards the upstream which will eventually cause stability problems for the whole string. The third stage, which is still underway for research and tests, is Cooperative ACC (CACC) which is basically ACC plus extra information from V2V (Vehicle-to-Vehicle) communication. Thanks to the delay reduction achieved with V2V information, CACC is able to maintain string stability even if the overall traffic speed fluctuates. This will significantly improve safety also. Although the BSM (Basic Safety Message) Part I [1, 2] was set as a standard to support cooperative collision warnings, it is not adequate for CACC control. It is therefore necessary to come up with a minimum set of messages which satisfy the needs of CACC as well as Active Safety (to enhance vehicle and driver safety with automatic control technologies).

PATH has developed and field tested passenger car and heavy-duty-truck CACC on freeways with other traffic, and in support of that work we have defined a set of V2V messages to support CACC functionality. Although more messages passed between vehicles will likely lead to better performance of CACC in general, there should be a minimum set of messages that is adequate for both CACC maneuverability and safety. It makes sense to minimize the size of such messages due to potentially significant overhead of V2V messaging in a practical traffic system since hundreds of vehicles may be within V2V communication range of the subject vehicle. This paper suggests such a message set. This set includes messages for maneuvers of individual vehicles within a CACC string, as well as for the coordination of vehicle maneuvers among multiple CACC strings in the same lane and different lanes in real traffic.

The messages include the following data:

- Data for longitudinal control CACC (Cooperative Adaptive Cruise Control) and platooning
- Data for lateral control (this is for future development although not implemented yet)
- Data for maneuvers of individual vehicles within a platoon (or string)
- Data for coordinated maneuvers among multiple platoons (or strings), including exchange of vehicles between two platoons (or strings)
- Data for fault detection and management for safety and maintaining platoon operation under anomalous conditions.

Some of the messages are already included in BSM I (Basic Safety Message I) and BSM II (Basic Safety Message II), but some are newly added for control and coordination purposes. This chapter explains the data sets sorted by their functionalities.

For communication purposes, the data to be transferred are encoded to the needed data types such as integers and then built into the communication packets. At the receiving end, the packets are resolved and decoded.

2. Data for Control and Active Safety

Control data include those from onboard sensors and J-1939 (Note to Xiao-Yun: J-1939 is a standard unique to heavy vehicles, light vehicle manufacturers do not use that standard, actually many technical people in the light vehicle industry are not familiar with this standard. Each light vehicle manufacturer has their own designation such as High Speed CAN, Low Speed CAN, etc. Please clarify this in this write-up) data bus and control commands which would directly affect the interactions among the vehicles in the platoon. The minimum set of data used for control usually will depend on the control design method. The set of data listed here are those PATH has used for platooning of passenger cars, buses and trucks to keep *practical string stability*.[3, 4, 5]. This represents 137 bytes plus 2 bits.

Data ID	Data name	Units	Range	Data Type	Data Sources	BSM I	BSM II	New Message
1.	Drive mode		1-8	Short int	Individual vehicle operation mode: 0-stop; 1-manual; 2-CC; 3-CACC; 4-const D-Gap Platoon			yes
2.	Vehicle Speed	m/s	0-70	float	Sensor measurement, CAN data	Yes		
3.	Desired t-Gap or G-Gap	s	0-5.0; 0-100.0	float	Driver from DVI on the lead truck			Yes
4.	Set speed	mph	5-70	float	Driver selection from DVI			Yes
5.	Distance to preceding vehicle	m	0-150	float	Estimated from sensor data			Yes
6.	Vehicle lateral position	m	0-100	float	Estimated from sensor data			Yes
7.	UTC Time	s		long int	From GPS	Yes		
8.	GPS Latitude	deg		**double**	From GPS	Yes		
9.	GPS Longitude	deg		**double**	From GPS	Yes		
10.	GPS Altitude	m		float	From GPS	Yes		
11.	GPS speed	m/s		float	From GPS	Yes		
12.	GPS Heading			float	From GPS	Yes		
13.	GPS number of satellites			int	From GPS	Yes		
14.	Position Accuracy	m		float	From GPS			Yes

14	Relative Speed to preceding vehicle	m/s	±30	float	Estimated from sensor data			Yes
15	Veh long Acceleration	m/s^2	±10	float	Sensor measurement, CAN data	Yes		
16	Veh lateral Acceleration	m/s^2	±10	float	Sensor measurement CAN data			Yes
17	Road grade	%	±20	float	Sensor measurement CAN data			Yes
18	Brake Pedal	%	0-100%	float	Brake pedal deflection; CAN data			Yes
19	Throttle position	%	0-100%	float	Acceleration pedal deflection; CAN data		Yes	
20	Fuel rate	g	0-100	float	CAN data			Yes
21	ACC Switch	On-off	0-1	bit	CAN data			Yes
22	Resume / Engaged ACC	On-off	0-1	bit	CAN data			Yes
23	Desired speed (control)	m/s	0-70	float	Vehicle speed control command			Yes
24	Desired torque (control)	N-m	0-5000	float	Engine torque control command			Yes
25	Desired deceleration (control)	N-m	0-10	float	Control foundation brake command			Yes
26	Desired transmission retarder torque (control)	N-m	0-5000	float	Control of engine brake command			Yes
27	Desired engine retarder torque (control)	N-m	0-5000	float	Transmission retarder control command			Yes

Data ID	Data name	Units	Range	Data Type	Data Sources	BSM I	BSM II	New Message
28.	Roll rate	Deg/s	-30 ~ +30	float	Sensor measurement CAN data			Yes
29.	Pitch rate	Deg/s	-30 ~ +30	float	Sensor measurement CAN data			Yes
30.	Yaw rate	Deg/s	-30 ~ +30	float	Sensor measurement CAN data			Yes
31.	Roll	deg	-180~ +180	float	Sensor measurement CAN data			Yes
32.	Pitch	deg	-90 ~ +90	float	Sensor measurement CAN data			Yes
33.	Yaw	deg	-180 ~ +180	float	Sensor measurement CAN data			Yes
34.	Steering angle	deg	-720 ~ +720	float	Sensor measurement CAN data			Yes
35.	Lateral position to lane center	m	-10 ~ +10	float	Estimated parameter			Yes

Some comments on the table:

Data ID 3: should be D-Gap instead of G-Gap (unless you defined G-Gap somewhere else)

Data ID 4; this is the only one in English system, everything else is in Metric. I understand that drivers in the US use mph when setting the speed request, but I am not sure if that needs to be transmitted as mph, especially for global standards. US manufacturers sell vehicles globally, and vice versa, and mph and kph are both used depending on the locality. If you decide to make this US based only, then there is no need to make the data element 'float', better use 'integer', that will save bits! Also, some vehicles let you set the speed lower than 5mph, and the upper limit could be higher than 70mph in the future. We have to set the standards based on future predictions.

Data ID 6: the range is 0-100m, is this the lateral position within the lane or roadway, and what is the reference point. You have to mention that, and I think you meant within the lane you should say with respect to center of the lane. If that's the case then 100m is too large, and I know that sensors are not capable of measuring with respect to roadway, thus must be within the lane. Please clarify, I also mentioned this point earlier.

Data ID 8-13: you can specify the range since it will not change.

Data ID 14-15: open up the range, with upcoming technologies and electric vehicles higher numbers can be achieved.

Data ID 18: should be 'Brake Pedal Position'. Can be integer since 1% accuracy will be more than sufficient driver cannot maintain constant position anyway.

Data ID 19: Throttle position and accelerator pedal position could be different in electronic throttle control (ETC) systems, and that is the case in great majority of vehicles and will be in CACC vehicles. Can be integer since 1% accuracy will be more than sufficient driver cannot maintain constant accelerator pedal position anyway. Throttle position is usually in degrees. Note: this is confusing as far as I am concerned.

Data ID 20: rate implies per unit of time, you mention gram, during what interval? Do you mean g/sec?

Data ID 28-29: could be higher in certain conditions.

Data ID 30: yaw rate could be much higher than specified when vehicle loses control, should be increased. System may need to react differently if and when vehicle is not under control such as on icy surface,

Data ID 34: could be integer to save bits!

Data ID 6 and 35: what is the difference between those two, it is not clear to me.

Another point I would like to make is (many people may not take this seriously and laugh at me), air bag status should be part of the message. Accidents will happen, and the system should behave in a certain way if there is an accident. For example, in the Tesla accident, the vehicle kept on running wildly until it hit a tree and stopped. It should have stopped immediately not to cause secondary accidents, as long as the necessary vehicle systems are still operational.

Xiao-Yun, these are important points, we are making a preliminary suggestion and we should be complete and correct as much as possible, please take these seriously.

3. Data for Coordination of Maneuvers within Platoon

This set of data is used for the coordination of the maneuvers of individual vehicles within a platoon, which is different from the platoon behavior as a collective. The data for coordination are usually defined by the control system designer. They are not from sensors. The control designer could define a particular meaning of a number which could represent a particular maneuver. To avoid confusion for the communication between vehicles of different makes, it is necessary to standardize this set of data. Broadcasting the current maneuver status is very important for control of individual vehicles and safety so that all the vehicles in the same string know what the others are doing right now. Obviously, one of the control strategies for the subject vehicle is to avoid any space-time conflict with other vehicles in the same string for safety, maneuvering efficiency and string stability.

Parameters for maneuver coordination would include: the coordination and indication of the maneuver (dynamic interaction) of an individual vehicle in the platoon. This information is also useful from a control viewpoint for the immediately following or preceding platoon to handle the dynamic interaction between platoons. The latter would include, but not be limited to: the time adjustment between platoons, and exchange of vehicles between platoons in the same lane (joining the front platoon from the back) and adjacent lanes (lane change). This represents 16 bytes of data.

Data ID	Data name	Units	Range	Data Type	Data Sources	BSM I	BSM II	New Message
1.	Veh unique ID			int	Designated anonymously by platoon leader for control purpose only			Yes
2.	Front cut-in flag		{-1,1}	Short int	Determined from remote sensor and GPS etc.; 1: cut-in; -1: cut-out			Yes
3.	Veh position in group		1 ~ 36	Short int	Determined by DSRC and GPS data			Yes
4.	Vehicle maneuver des		0 ~ 127	Short int	Designated by platoon leader			Yes
5.	Vehicle maneuver ID		0 ~ 127	Short int	Actual maneuver executed, determined by individual vehicle			Yes
6.	Distance to lead vehicle	m	0 ~ 100	float	Estimated from communicated GPS data			Yes
7.	Distance to the preceding vehicle	m	0 ~ 100	float	Estimated from communicated GPS data; the preceding vehicle is the platoon mate; not the cut-in vehicle(s)			Yes

Data ID 6: is lead vehicle the platoon lead vehicle, if yes then the range of 100m is not sufficient.

Data for Fault Detection and Handling

Parameters to represent the current health condition of the control system are very important information for other vehicles in the same platoon and other platoons nearby (in the same lane or adjust lane) to make correct decisions for safe maneuvers. This information should include the fault types and the means for handling the fault. The outcome of the handling would be a proper control mode or relevant maneuver to avoid a collision.

It is noted that the Vehicle Fault Mode is represented with a single long integer. The reason is explained as follows: there could be many possible faults/error that could affect automated vehicle control; to name a few: V2V communication drops, lidar/radar detection, other sensors (speed, gyro, road grade, GPS, …), network switch, CAN and interface, control computer, control software including database, DVI (Driver Vehicle Interface), engine torque control, engine retarder control, torque converter, transmission retarder control, and foundation brake control, etc. Since each component would affect platooning in different aspects and at different levels, all such information should be built into the Vehicle Fault Mode parameter. To achieve this, one could use a bit-map with each bit (assumed a conventional sequence of order for all possible faults) corresponding to a specific fault. Then this bit map could be converted into a long integer (8 byte) which can represent the fault status of 63 different components. To avoid confusions in the fault mode definition, it is necessary to have a standard which defines the threshold of fault. As examples, if inter-vehicle communication continuously drops for longer than 1s, it is considered as a communication fault; if the distance estimation discrepancy is over 10% of the actual distance, it is considered as a distance measurement fault; if the relative speed estimation error is over 10% of the actual relative speed, it is considered to have a relative speed measurement error; etc. This quantification should be specified for all parameters that are critical for the control. This represents 12 bytes plus one bit.

Data ID	Data name	Units	Range	Data Type	Data Sources	BSM I	BSM II	New Message
1.	Veh fault mode ID			long int	Determined by individual vehicle			Yes
2.	Communication count		0~127	int	For communication fault detection			Yes
3.	Brake Lights or Switch	On-off		bit	Sensor-CAN	Yes		

4. Data for coordination between Platoons

This data set is for use in coordinating maneuvers between platoons, including transfers of individual vehicle between platoons, as well as platoon actions as an entity. It could be used for V2V communications between the leaders of the two platoons. However, due to power limits and limited range of V2V communication, it may also be passed between the last vehicle in the lead platoon and the leader of the following platoon. Since each vehicle would have a chance to the leader or the last vehicle in a platoon, for convenience, it would be necessary to include this 21-byte set of data in the V2V communication packet.

Data ID	Data name	Units	Range	Data Type	Data Sources	BSM I	BSM II	New Message
1.	Time stamp	hr:min:s: ms	0-23 0-59 0-999	int:int: int:int	Synchronized (or universal) time based on but different form GPS UTC time			Yes
2.	Group ID		0-127	Short int	Designated by roadside coordination manager			Yes
3.	Group size		0-31	Short int	designated by roadside coordination manager			Yes
4.	Group mode		0-31	Short int	Following mode of the platoon; designated by the coordination manger			Yes
5.	Group maneuver des		0-127	Short int	Designated by coordination manager, desired (such as join: acceleration to close the gap to the front platoon)			Yes
6.	Group maneuver ID		0-127	Short int	Representing actual maneuver; designated by platoon leader			Yes

5. Concluding Remarks

Communication data is critical for connected automated vehicles. On one hand, it is desirable to pass as much information as possible between vehicles and between the vehicle and the roadside coordination manager. The latter will be necessary if the market penetration of connected automated vehicles is high, but may not be necessary when the market penetration is low. On the other hand, more information passing would mean more communication overhead considering so many vehicles are broadcasting and receiving within the DSRC range. For control performance and safety, it is necessary to have a minimum communication data set. The suggested data sets above are initial suggestions based on the experience in connected automated vehicle control research at California PATH for the past thirty years. Different vehicle types, including both light and heavy duty vehicles, have been taken into consideration.

If we assume the following data size: short int: 1 bytes; int: 4 bytes; long int: 8 bytes; float: 4 bytes; long float: 8 bytes, the total packet size to contain the suggested data will be 186 bytes plus 3 bits.

References

[1] SAE J2735: Dedicated Short Range Communications (DSRC) Message Set Data Dictionary, SAE International

[2] SAE J2945/1: On-Board System Requirements for V2V Safety Communications, SAE International

[3] X. Y. Lu and K. Hedrick, 2004, Practical string stability for Longitudinal Control of Automated Vehicles, Int. J. of Vehicle Systems Dynamics Supplement, Vol. 41, pp. 577-586

[4] X. Y. Lu, S.E. Shladover, Integrated ACC and CACC Development for Heavy-Duty Truck Partial Automation, to be presented at 2017 American Control Conference, (ACC-17), May 24-26, Seattle, WA, USA

[5] X. Y. Lu and J. K. Hedrick, 2002, A panoramic view of fault management for longitudinal control of automated vehicle platooning, *Proc. of the 2002 ASME Congress,* Nov. 17-22, New Orleans