Field Test of In-Vehicle Speed Harmonization to Reduce Traffic Bottlenecks

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1. Introduction

The Federal Highway Administration's Saxton Traffic Operations Laboratory (STOL) would like to conduct a field test of speed harmonization (SH) strategies to mitigate the congestion produced at traffic bottlenecks. Prior experience in several European countries and Australia has shown that the effects of highway capacity reductions caused by lane drops and merging or weaving sections can be mitigated if the approaching traffic is gradually slowed down before it reaches the bottleneck location. Computer simulations of these strategies by researchers working at STOL have been promising, but the strategies need to be tested in the field to determine how well they can work in practice. This is a conceptual test of the technical implementation of speed harmonization to be accomplished over a small region of freeway and a short period of time as a proof of principle. If successful a larger field operational test will validate simulated applicability and market penetration requirements.

Two different approaches for modifying the speeds of the test vehicles to achieve speed harmonization will be tested. The primary focus is on three test vehicles that have been equipped with an I2V CACC (Cooperative Adaptive Cruise Control) system such that the real-time recommended maximum speed for each section of highway is communicated to the vehicle as the set speed value for its ACC (Adaptive Cruise Control) system, and the ACC system will then ensure that this speed is not exceeded. Several additional vehicles may be driven by test drivers who will receive the maximum advisable set speed value by display on a smart phone (either visual or audible display), and the test drivers will be responsible for trying to avoid exceeding these set speeds.

2. Public Outreach

Whatever is to be tested in the field, public outreach is an important issue. Simply driving three vehicles side-by-side to block the other traffic and force it to follow the test vehicles is likely to cause public complaints. To avoid this, the following approaches may be adopted:

<u>*Before the test*</u>:

- Coordinating with VDOT closely on the public outreach issues; consulting with VDOT about their experience of public outreach for construction of the Springfield interchange;

- Vehicle preparation: mount a sign on the back of the test vehicles with something like “Experimental Vehicle”, “Test in Progress”, or “May reduce speed, follow with care”;

During the test

- Always keep VDOT staff, particularly Traffic Ops staff responsible for the relevant I66 and VA267 sections on board; and keep them updated about any actions to be taken in the field; it would be necessary to invite VDOT Traffic Ops engineers to the test site during the tests;
- Using two VMS signs, one at beginning of the test section and one at the end of the test section to inform the public drivers about the start point and end point and duration of the tests;
- Only use vehicles with signs as proposed above for the tests so that the drivers of the following vehicles will recognize what is going on.

3. Test Range on I-66:

The proposed test site for the field test is on I-66 and SR-267 eastbound inside the Beltway, beginning with the approaches to the merge of these two highways and continuing for 3.5 miles downstream of the merge to N. George Mason Drive, including the reductions from four lanes to three and from three lanes to two. From the algorithm point of view, the advised speed will be provided at 7 locations along the two highways as the test vehicles pass these locations during the evening peak period.

The reason for doing so is that high density and low speed traffic appears persistently in the PM peak hours in that stretch until traffic reaches N. George Mason Drive based on our combined traffic data analysis. If all the test vehicles enter from the onramp at N. Sycamore St. and conduct an immediate lane-change blocking traffic in both lanes, it will likely adversely affect traffic flow. As a consequence, the test vehicles will not help to produce flow close to the capacity flow in the “tube” section downstream of Sycamore. Therefore, the only practical entrance for the test vehicles is at the I-66 onramp from Rt. 267. Thus, it will take a long time for the test vehicles to turn around and get into the test section again.

4. Test Vehicles

Test vehicle will include equipped vehicles and non-equipped vehicles.
The equipped vehicles are required to have the following capabilities:

- CACC vehicles able to operate in all traffic phases: from free-flow to Stop&Go
- CACC vehicle can use VSA as the set speed for control
- GPS for timing and real-time location detection
- 4G modem link with central computer in SAIC Lab
- Display to the driver at least the following parameters:
    - Set speed
    - Practical vehicle speed
    - Distance to front vehicle

- Time headway

If some other non-equipped vehicles are available in addition to the 3~5 equipped vehicles, it is possible to use smart phones as set speed displays and I2V communication devices. Drivers will manually operate those vehicles by choosing a proper speed based on the set speed from VSA and the actual traffic speed around them.

The non-equipped vehicles will have smart phone further developed for display to the driver of the above parameters and for real-time communication with the central computer at SIAC Lab.

5. Test Scenarios and Potential Effect

This section analyzes different test scenarios with respect to the number of test vehicles available. Traffic performance is a macroscopic level concept which relies on continuous effective impact on traffic over both time and space. In general, the more test vehicles available, it is more likely that tests will have continuous impact on traffic. We will provide the minimum number of test vehicles for the given test site in Appendix, which could generate continuous impact on traffic from a macroscopic level for certain period of time. It is assumed henceforth that the test will be conducted with I2V communication.

The test vehicle with ACC/CACC capability can be driven manually or automatically. The non-equipped vehicles will be driven manually. Either way will need to have set speed display to the driver. In the latter case, the VSA value supplied by the central computer will be used as the set speed of the test vehicle.

If the number of test vehicles is limited to 3, they can be used to show that those three vehicles can lead the traffic behind them if they are driven side-by-side, prohibiting other vehicles behind to pass by. This scenario could test the impact range of the test vehicles. More specifically, if the test vehicle slows down more than general traffic, it will affect traffic further upstream. However, as the leading vehicles slow down, the test vehicles are likely to create shockwaves behind if their speed reduction is over certain threshold, which should be avoided in the test. If there are 5 test vehicles, the other two should be added in a certain range of the upstream. This range (time gap and distance) is actually the impact range of the downstream test vehicles, which will be determined through multiple tests. With the two upstream test vehicles, such range will be easier and more accurate to determine than just using the fixed roadside sensors (trailers). Here the test vehicles used as probe will be beneficial since they provide information in the moving window around them, which the roadside sensors may not be able to reach.

It is necessary to note that the test is unlikely to produce results with improved traffic throughput with only 3~5 test vehicles. The effect on SH is also very limited in range. The reasons are as follows:

(a) If there is not much space in front of the test vehicles, they cannot increase speed significantly since the downstream traffic will prohibit them from doing so; if the test vehicles first slow down more to get more wriggle room in the front and then accelerate later, they have already reduced the flow. The test vehicles could, however, slow down for a longer period of time to block the traffic into the "tube" section so that the high density traffic already there could be discharged. Once the discharge wave front arrives, the test vehicles could take the lead for acceleration.

(b) The impact of three vehicles driver side-by-side is limited due to the following factors:
- Traffic following the test vehicles have time delay, large variation in driver behavior, which means that the effect of the test vehicles on the vehicles following them will diminish towards upstream;
- Once the test vehicle passed onramps and off-ramp, the driver behavior at the onramp/off-ramp will have strong impact on mainline traffic, particular merging vehicles from onramp, and vehicle lane changing for leaving the freeway. Those effects will likely override the impact of the test vehicles further downstream.

This indicates that multiple test vehicles are necessary to generate continuous impact on traffic for certain period of time. In the Appendix, the minimum number of vehicles necessary to do so is estimated.

6. Infrastructure-Based Traffic Data Collection Requirement

Sensor requirements depend on the SH strategy to be tested. Each sensor needs to log data to the local computer and send the data in real time to the central computer through wireless communication. The update interval will be between 5 and 30 seconds, which the trailers can provide.

For Speed Harmonization, the trailer locations are indicated in Figure 1, which includes 6 trailers. This will be confirmed through simulation.

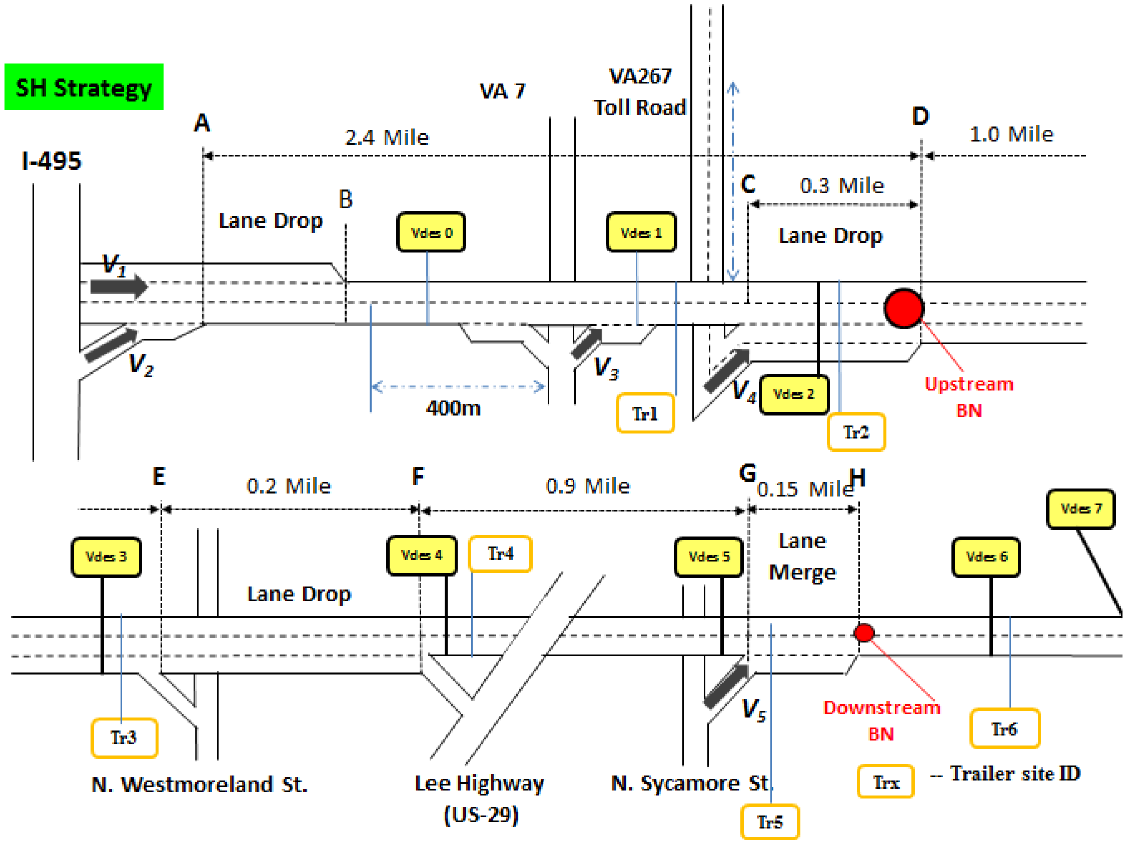

Figure 1. Speed Harmonization strategy: Sensor and VSA change points

7. Preparation of Test

Before field test start, it is necessary to make sure the overall system is well integrated and working properly.

The following is a check list before field testing using fully equipped vehicles:

- On vehicle power supply and computer system work reliably
- On vehicle display works properly
- On-vehicle data readings available:
  - GPS reading
  - Speed reading
  - Data logging of GPS and speed data and communication data
- Central Control Computer
  - Operating system suitable for real-time operation
  - Communication module to drive the wireless modem works properly
  - Timing for data retrieving and sending
  - Algorithm module running correctly and robustly for all possible test scenarios and all traffic situations
  - Data logging of all sensor data and communication data

    - To update the VSA value for those vehicles using wireless communication
- 2-way communication between each test vehicle and the Central Control Computer
    - Update rate
    - Speed passing from the vehicle to the Central Computer
    - Desired VSA values passing from the Central Computer to each vehicle
- Road sensor
    - Sensor detection
    - Data retrieving and logging
    - Data passing to central Computer
- I2V CACC operation test
    - Test the control system by manually setting the speed at TFHRC
    - Test the control system of a single test (CACC) vehicle by manually setting the speed in real traffic to identify the performance of the controller, which should include both free-flow traffic and Stop&Go traffic
    - Test the control system by passing the set speed from the central computer at STOL to make sure the vehicle follows the set speed (should be set very low)
    - Test the control system of a single test (CACC) vehicle by passing the set speed from the central computer in real traffic to identify the performance of the controller, which should include free-flow traffic and Stop&Go traffic

8. Time Frame and Test Procedure

The field testing will be conducted between February and June 2014, with the variable speed advisories only being applied during the evening peak period for traffic moving in the eastbound direction in the test section.

It is assumed that the tests will only be conducted on weekdays. .

Week 1 ~ 6: (a) test and tuning of all sensor detection, data synchronization, data logging and passing; (b) test real-time data processing and traffic state parameter estimation; (c) test SH algorithm real-time operations – the VSA vector generated at all the changing points makes sense; (d) developing smart phone application to read GPS information and to communicate with the central computer;

Week 7 ~ 10: (a) Test to verify that vehicle sensor (speed and GPS) readings and communication link work properly; (b) Test and debug one vehicle only in the freeway stretch suggested below to make sure the integrated system works properly in the real environment as in the check list above;

Week 11~12: Test and debug each vehicle individually to make sure the overall system works properly for each vehicle as expected;

Week 13~14: Test of each V2I CACC vehicle functionality;

Week 15~17: Gradually increase the number of vehicles in the system for debugging;

Week 18~21: Full scale field test and data collection.

Appendix – Technical Parts

This Appendix includes the following technical parts of the test plan:

- Concept of Operation
- Overall System Structure
- Smart Phone Development
- Number of Vehicles Needed to Generate Continuous Impact on Traffic
- Test Scenario Simulation

1. Concept of Operation

From the algorithm point of view, the advised speed will be provided at 7 locations along the two highways as the test vehicles pass these locations during the evening peak period. For the I2V CACC vehicles, since the advised speed is used as the *set speed*, the determination of the actual speed trajectory of the test vehicle will depend on the speed and distance to its immediate front vehicles. If there is no vehicle in front within the desired car following range, the test vehicle will be driven at the set speed by the ACC/CACC control (the VSA speed); but if there is a vehicle in front, the actual speed of the test vehicle will be lower than the set speed. Besides, for speed harmonization purpose, it is not desirable to change speed too often since frequent changes will disturb the traffic flow from a macroscopic viewpoint, considering the response delays of surrounding drivers.

VSA display to the driver is necessary if the vehicle is controlled by I2V CACC or operated manually. For driver acceptance with in-vehicle display, providing VSA based on sections (and over a certain period of time) should be more acceptable since this could minimize driver attention-distraction problems. Besides, the VSA speed values should be rounded to multiples of 5 mph.

The locations for the VSA speed recommendations are shown in Figure 1 for speed harmonization. Once the test vehicles reach the neighborhood of that point based on GPS reading, the set speed of the CACC vehicle will automatically change to the suggested speed.

The suggested speed values will change in response to changing traffic conditions, but changes will be no more frequent than once per minute and be no larger than 10 mph between consecutive sections.

2. Overall System Structure

The overall system structure for the test is shown in Figure 2, which includes the test vehicle, traffic detectors, on-vehicle computer and display on each vehicle, wireless communication unit (such as 4G modems), and a central control computer. They are linked with the central computer located at the STOL using 4G wireless modems (V2I).

This 2-way communication can pass the advised speed to the test vehicle and the actual vehicle speed can be passed to the Central Computer, where it will be used as a probe vehicle speed sensor. This is beneficial in the cases when the test vehicle is driving at a lower speed than the set speed due to slow traffic in its immediate front.

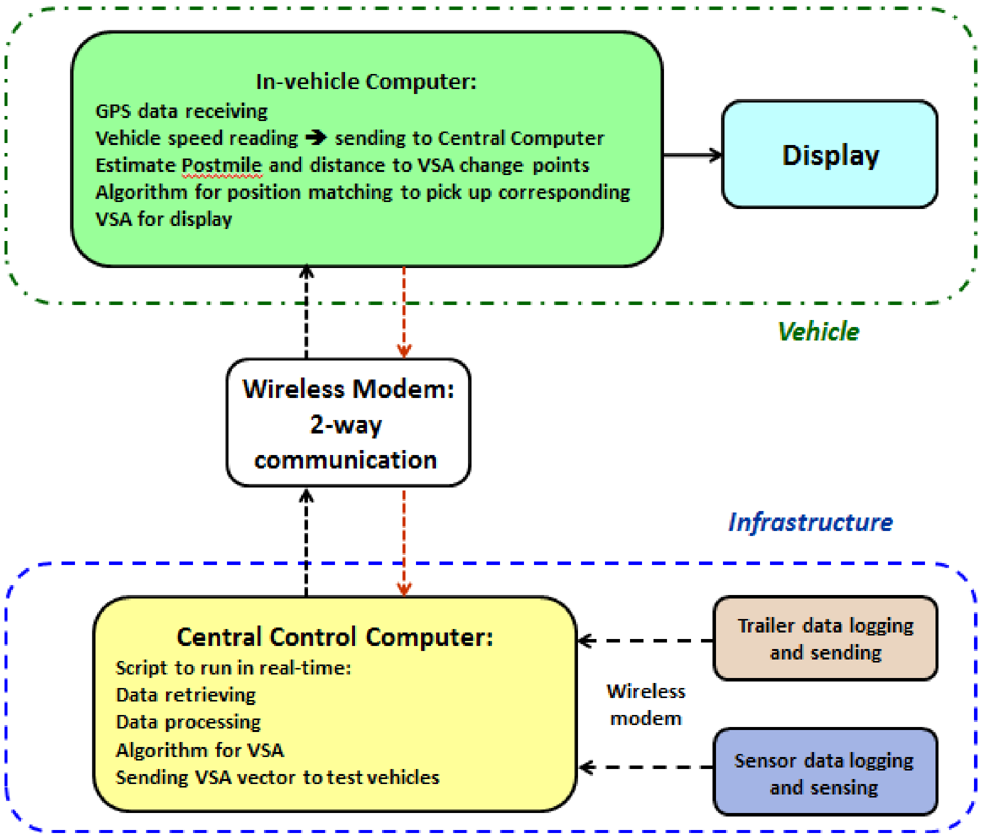

Figure 2. Concept of Operation - Overall system structure

3. Smart Phone Development

Most smart phones have API (Application Programming Interface) capability using SDK. This would need some further development on smart phones to have the required functions. However, practical feasibility of this approach will depend on the permission of FHWA.

It is noted that the smart phone is not supposed to be operated manually for this test. Using the wireless data link, the central control computer could send the VSA vector to the smart phone. However, a smart phone application still needs to be developed to access the GPS coordinate internally in the phone, to access the message sent from the central computer including the VSA value by location vector, to match the phone's current GPS coordinates with the GPS coordinates attached to the VSA vector to select the proper VSA value based on location, and to display the set speed. It is possible to develop an application to receive information from the central computer using SSH client. With the development of these applications, a smart phone could perform the functions otherwise performed by the computer, GPS system, and the 4G modem on the equipped vehicles, providing the possibility of issuing VSA messages to drivers in a larger number of unequipped vehicles.

4. Number of Vehicles Needed to Generate Continuous Impact on Traffic

The following is a back-of-the-envelope estimation of the minimum number of vehicles needed to generate some continuous impact on traffic in both time and space. This is the minimum requirement to evaluate the performance impact of VSA or speed harmonization on the traffic.

According to the road geometry, 3 vehicles will be necessary for the section upstream of Lee Highway (US 29) due to 3 lanes. For the stretch downstream, at least two test vehicles will be necessary. For this test range, it would take about 60 minutes for a test vehicle to turn around based on the VBox data time stamp.

For the test vehicles to produce a significant measurable effect on traffic flow, it is assumed that the upstream range that each test vehicle can influence is 500 m. We would therefore need approximately 3 pairs of (or 6) vehicles in each mile. Then the 3.5 mile test section would need approximately 17 pairs of (or 34) vehicles in the system to have a sustained effect on traffic. The average travel time to traverse the test section was 833 s (or 14 min) based on VBox data. To generate a 30 min effective impact on traffic, we would need at least 35 pairs of (or 70) test vehicles to run in the 2 mainline lanes. We would need another 5~10 vehicles to run on the 3rd lane in the section between the Rt 267 onramp and Westmoreland off-ramp. Adding them together, we would need about 80 test vehicles to generate 30 min of sustained impact on traffic. However, if the impact range of a pair of test vehicles is about 1000 m rather than 500 m, then the number of test vehicles could be reduced to 40. All the test vehicles could be used as probe vehicles to pass to the central computer their speed and GPS location etc. As we discussed before, this could be beneficial for the case when the test vehicle is driving at a lower speed than the set speed due to slower traffic immediately ahead.

5. Test Scenario Simulation

This scenario can be simulated with MicroSDK in Aimsun. The project team has found a way to do so with some minor modification in the sense that the 3~5 test vehicles will not enter the system from an onramp, instead, they will enter the system from the most upstream point on the I-66 mainline. In this way, modeling of the onramp behavior and lane change behavior of the test vehicles can be avoided.