ESC Performance of Aftermarket Modified Vehicles: Testing, Simulation, HIL, and the Need for Collaboration

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ABSTRACT

The enactment of FMVSS 126 requires specific safety performance in vehicles 4,536 Kg (10,000 pounds) or less using an Electronic Stability Control (ESC) system as standard equipment by 2011. Further, in 2012, the regulation requires vehicles that have undergone aftermarket modification to remain in compliance with the performance standard. This paper describes: • a brief overview of the standard and its implications • the collaborative approach used in the first successful approach in meeting that requirement by a lift kit manufacturer o a Hardware In the Loop (HIL) test alternative for establishing a reasonable expectation for a vehicle to demonstrate compliance after modification. • Collaborative challenges overcome: o aftermarket manufacturers seeking information sharing with OEMs and Tier One suppliers: o respecting the intellectual property of OEMs and Tier One suppliers o maintaining the integrity between tool competitors and their customers in cross-collaborative efforts

Introduction

The historic relationship between Original Equipment Manufacturers (OEMs) and the Aftermarket has been tenuous. On one hand, there have been widely recognized mutually beneficial relationships (Roush/Ford, AMG/Mercedes, Callaway/Chevrolet, etc) but conversely, OEMs often see the Aftermarket companies as adulterers of their pristine creations. Clearly, the Aftermarket does not exist without OEMs. Yet just as definitively, OEMs have often benefited from their products being deemed readily accessible for modification.

Increasing product complexity and integration of vehicle systems has magnified this dichotomy. The expanding scope of government regulations has provided another impetus for examining and improving existing business interactions. One example is the US National Highway and Transportation Safety Agency (NHTSA) Regulation FMVSS 126 that provides definitive performance requirements for Electronic

Stability Control (ESC) systems while mandating their presence on all vehicle with a mass less than 4,536 kg (10,000 lbs). It specifically mentions aftermarket-modified vehicles, granting an extension in time before requiring conformance to the standard, *"... for vehicles built in two or more stages and altered vehicles (70 FR 7464) excluded from the requirements for phase in are permitted an additional one year for compliance (i.e., until Sept. 1, 2012)."*[1]

Yet ESC and the challenges presented by FMVSS 126 offer excellent opportunities for new and innovative interactions between OEMs and the Aftermarket. But as David Cole, President of CAR has said, *"Collaboration in many ways is an unnatural act. It's not easy to work together as a team. What we are looking at is reinvention of the business model and changing how you think about the way we do things. Clearly, there are reasons why the OEM and Aftermarket need to come together and collaborate more effectively*".

One set of reasons can be seen in the Light Duty Truck market. This segment accounts for nearly 35% of annual vehicle sales in North America. In 2008, that amounted to $4.7 billion to manufacturers and $13 billion in retail transactions. Aftermarket accessories represented a large portion of that total. Wheels, tires, and suspension upgrades alone accounted for $1.3 billion in manufacturer sales and an estimated $3.6 billion in retail sales. New vehicle purchasers spent an average of $1,831 on accessories. Remarkably, 78% of all accessories are purchased within one month of purchasing the vehicle. [2]

These purchases are made through the new vehicle dealer, an aftermarket retail store, a mail order catalog, or the internet. Notably, a majority of light duty truck owners indicated they prefer to purchase accessories from their new vehicle dealer. The reasons included price, availability, quality, reliability, durability, and installation. Even more notable, a full 12% indicated that vehicles that were accessorized were their sole reason for visiting the dealership. An additional 23% said they were partially influenced by the availability of accessorized vehicles. The business motivations for collaboration are evident. [2]

However, for aftermarket companies to truly partner with OEMs, they must demonstrate their commitment to the standards that each OEM has established for its brands. The qualities that distinguish each brand encompass a wide range of characteristics, but one aspect that is common to all brands these days is safety. One way that an aftermarket supplier can demonstrate its capabilities to provide a safe modified vehicle is to demonstrate the altered vehicle's compliance with federal safety regulations. One possible way for a tire, wheel, or suspension aftermarket company to accomplish this is to provide data that supports the reasonable expectation for the modified vehicle to meet the performance requirements of FMVSS 126.

In order to effectively explore the possibilities, one must first understand the requirements of FMVSS 126 and how the manufacturers seek to establish a reasonable expectation of all the variations of their production run being in compliance.

FMVSS 126

The primary motivating factor behind FMVSS 126 is that it saves lives. Several studies have shown tremendous reductions in fatalities and serious accidents in vehicles equipped with ESC. For example, a 2004 report issued by the Insurance Institute of Highway Safety (IIHS) stated: *"Based on all police-reported crashes in 7 states over 2 years, ESC reduced single-vehicle crash involvement risk by approximately* ***41 percent*** *and single-vehicle injury crash involvement by* ***41 percent****... Based on all fatal crashes in the United States over 3 years, ESC was found to have reduced single-vehicle fatal crash involvement risk by* ***56 percent****"*. [3]

FMVSS 126 defines both the equipment required and a set of performance measures that must be met by the affected vehicles. It mandates that ESC must have the ability to independently modulate the brakes as well as reduce the delivered engine torque. [4] The performance attributes are aimed at yaw stability, demonstrating directional control while precluding rollover. [5] Sayers and Mather of Mechanical Simulation have developed a concise description of the testing procedure:

"After completion of a number of control checking and conditioning tests for the brakes and tires, FMVSS 126 requires three sets of tests. First is a "Slowly Increasing Steer Test" (S7.6). (S7.6 refers to the section in the standard.) Three tests are performed in which the vehicle is traveling at 80 km/h and the steering angle is ramped at 13.5 deg/s until a lateral acceleration of 0.5 g is reached; three similar tests are also done in the opposite direction (−13.5 deg/s to −0.5g). Data from the six tests are processed to determine the average steering wheel angle associated with a lateral acceleration of the vehicle mass center of 0.3 g. That steering wheel angle is designated ***A*** and is used to define and evaluate tests that follow.

Next, two series of "Sine with Dwell" tests are conducted with "a steering pattern of a sine wave at 0.7 Hz frequency with a 500 ms delay beginning at the second peak amplitude" (S7.9, see Figure 1 and Figure 2, copied from p. 17315 [1]). The sine amplitude d is (Gain × ***A***), where the initial Gain is 1.5 (S7.9.3), and is increased for each test by an increment of 0.5 (S7.9.4) until the final run. The final run in a series is reached when the amplitude d is greater than 270°. If the amplitude d is greater than 300°, then the amplitude for the final run is reduced to 300° (S6.9.4).

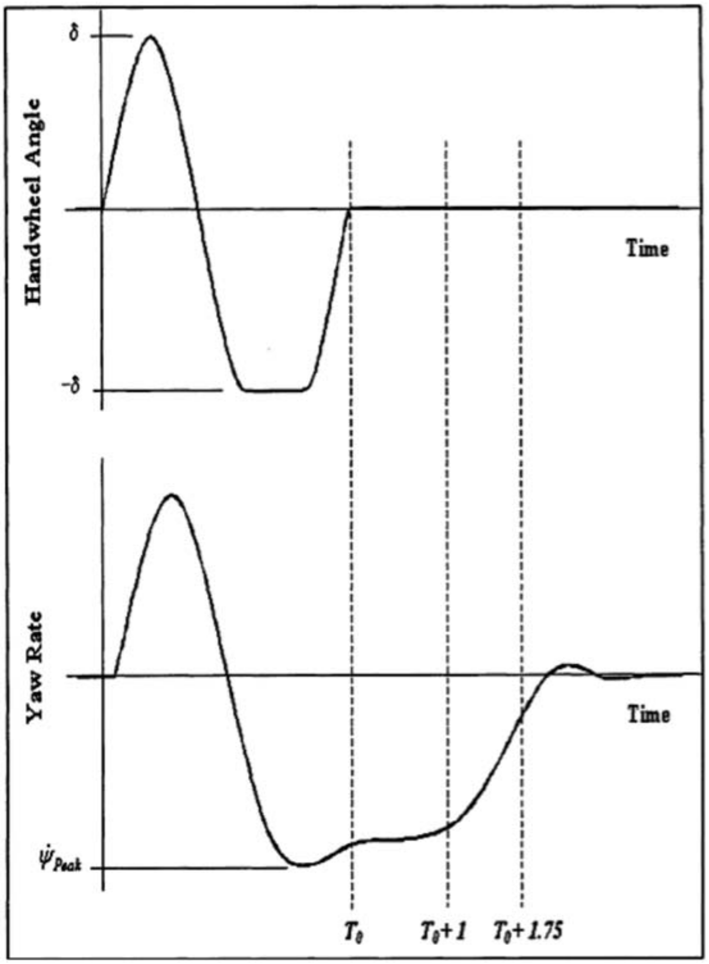

Figure 1. Steering wheel position and yaw rate are used to assess lateral stability.

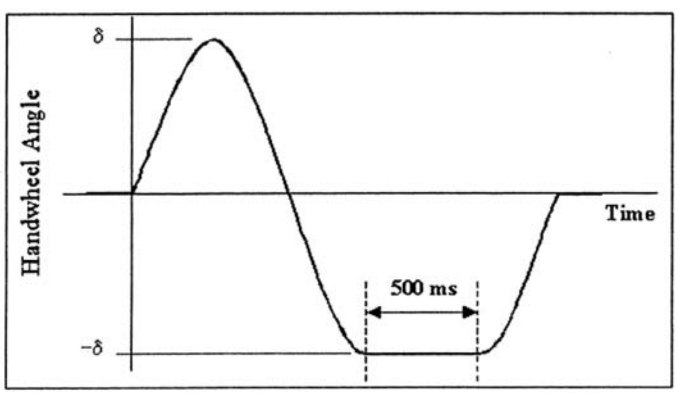

Figure 2. Sine with Dwell steering profile (p. 17315 from Federal Register).

The success or failure of each test in the series is based on the vehicle state at up to three times during the run (see Figure 3). A peak yaw rate is obtained by starting to scan the vehicle yaw rate when the steering wheel angle changes sign (0.71 sec after the Sine with Dwell starts).

1. At T = 1.07 sec (after the start of the Sine with Dwell), if the Gain is 5.0 or greater, then the lateral displacement of the vehicle mass center must be 1.83 m (6 ft) or greater relative to the start of the test for vehicles with GVW of 3,500 kg or less (S.5.2.3). If the displacement is less, then the vehicle fails the test. For vehicles with GVW greater than 3,500 kg, the required lateral displacement is 1.52 m (5 ft).

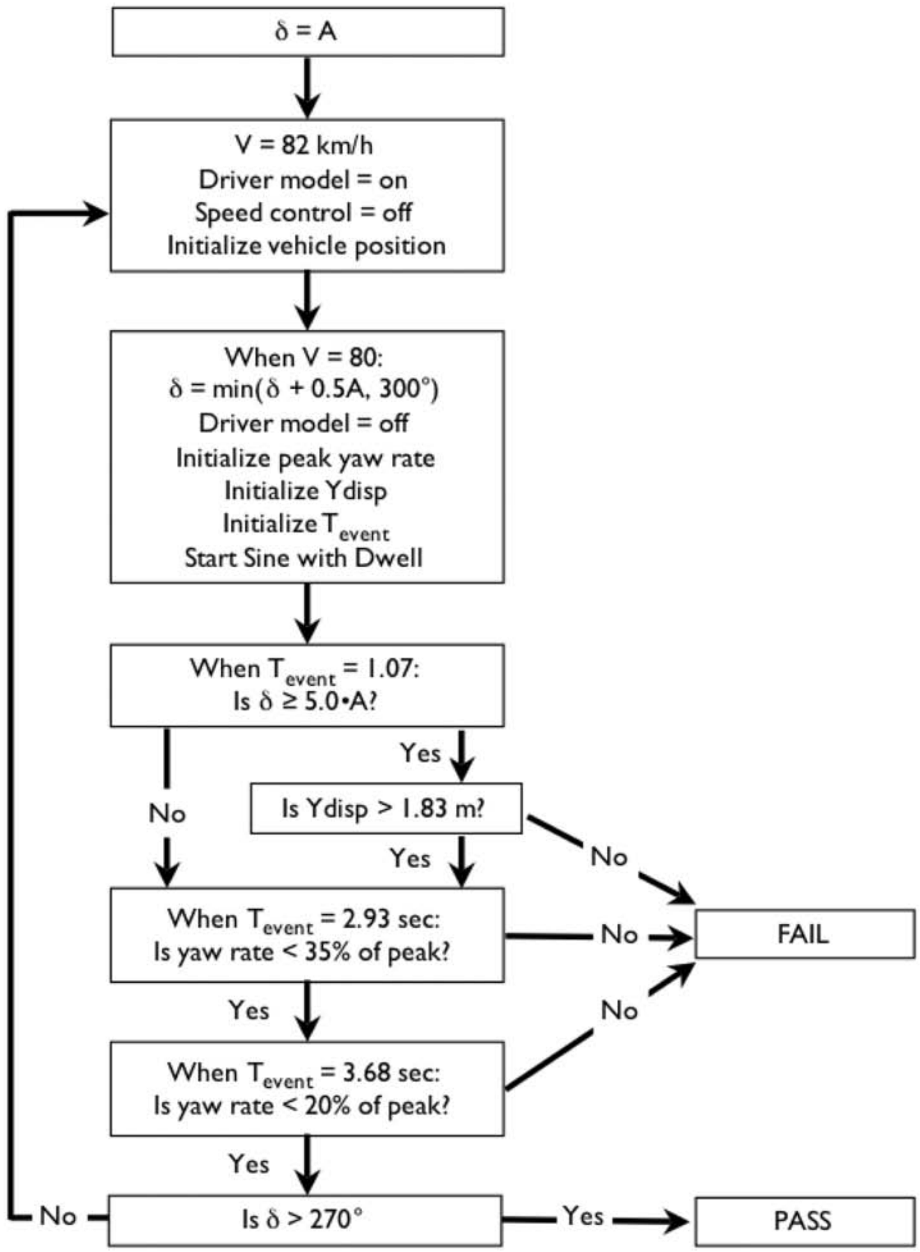

Figure 3. Flow chart for the Simulated Sine with Dwell test series

2. The instant yaw rate at T = 2.93 (1.0 sec after the steering stops) must be 35% of the peak rate or less (S5.2.1, see Fig. 1). If the instant yaw rate is higher than 35% of the peak yaw rate, then the vehicle fails the test.

3. The instant yaw rate at T = 3.68 (1.75 sec after the steering stops) must be 20% of the peak rate or less (S5.2.2, see Fig. 1). If the instant yaw rate is higher than 20% of the peak yaw rate, then the vehicle fails the test.

If the vehicle is tested to the final run in each direction and does not fail, then the vehicle passes the test." [5]

Clearly, this is an involved procedure that requires dedicated equipment and special test facilities.

Physical Testing

Despite the complexities inherent in this test regimen, OEMs routinely run samples of their vehicles through this process. The associated costs and limited applicability, however, present additional challenges to Aftermarket Manufacturers. Despite these hurdles, one Aftermarket Manufacturer, ProComp, successfully demonstrated the compliance of one of their vehicles with FMVSS 126 at an independent test facility. The tested vehicle was a 2008 Chevrolet Silverado Z71 equipped with a ProComp 6″ Lift Kit. A comparison of production and modified vehicles is pictured below in Figure 4. The lifted truck is shown next to a stock 2008 Chevrolet

Figure 4. Modified and standard 2008 Chevrolet Silverado Z71's

Silverado Z71. The modified vehicle displayed a 10″ higher front bumper height and a 4″ higher rear bumper height in a side-to-side comparison. Additionally, the increase in the front track width is especially noticeable.

The modified vehicle underwent FMVSS 126 testing at the Transportation Research Center (TRC) in Marysville, OH. Some of the specialized equipment required is shown in Figures 5 and 6.

Figure 5. Modified vehicle with custom outrigger

Figure 6. Steering "robot" with instrumentation

In order to successfully demonstrate the compliance of their lift kit design with FMVSS 126, ProComp had to go through the process depicted in Figure 7.

Each step along the way led to a significant commitment of ProComp resources in both time and money. Yet at the outset, there was no guarantee of success, just a determination to achieve the end goal of demonstrating compliance. Fortunately, with the extensive upfront work of their design team, there was no need for an expensive redesign prior to actual testing at TRC.

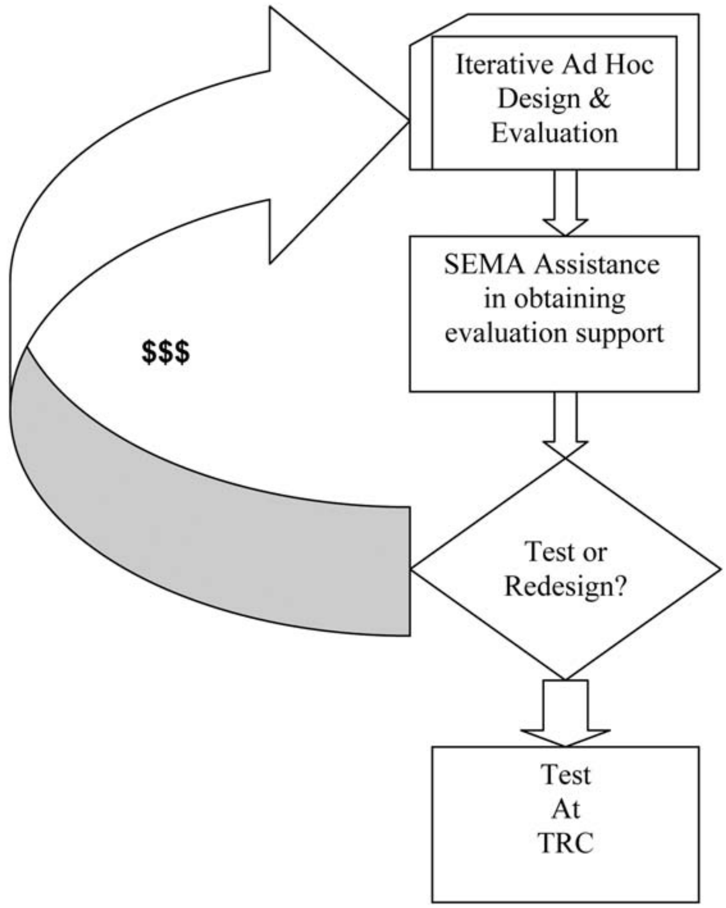

Figure 7. High-level physical test process

The collaboration that occurred in this program existed solely in the Aftermarket, with the Specialty Equipment Market Association (SEMA) helping ProComp find the right partners to meet their needs and fill-in gaps in expertise.

Pure Simulation

Even with the OEMs running physical tests, they are increasingly developing simulation-based techniques to better examine system robustness, design sensitivities, and test variability. It is an aim of SEMA to facilitate the collaborative use of these methods by its Aftermarket members so they can use the development tools of their larger clients and readily exchange information with their OEM partners.

As discussed in the paper by Sayers and Mather, pure simulation lends itself to an efficient analysis of a well-defined vehicle running CarSim: "Most of the conditions covered by FMVSS 126 involve setting up the vehicle. This involves checking the electronics, conditioning the brakes, conditioning the tires, and making repeated tests to account for uncontrolled test variations. A typical CarSim model is set up with the vehicle properties (including tires and brakes) in the "ready to test" condition, so these steps are not necessary. Instead, the main interest is in setting up the sequence of Sine with Dwell tests, to allow a one-click run option to obtain a quick idea of how the simulated system would perform in the FMVSS 126 test. In versions of CarSim prior to version 7, this sequence of tests might have been simulated with a batch of runs. Because the steering wheel amplitude depends on the result of the initial ramped steer tests (based on the steering wheel angle observed at Ay = ±0.3 g), different amplitudes are needed for every vehicle or configuration being simulated. The process would have to be adjusted by hand, or automated by combining CarSim with external software such as Simulink.

With the introduction of VehicleSim (VS) commands in CarSim 7.0, the entire sequence can be handled automatically in a single run. An example was posted on the www.carsim.com web site in September 2007, along with an earlier version of this memo.

Some improvements in the VS commands that are available in CarSim 7.1 have made the control simpler and more modular. To demonstrate this, CarSim 7.1 comes with example runs made with and without a simple ESC controller

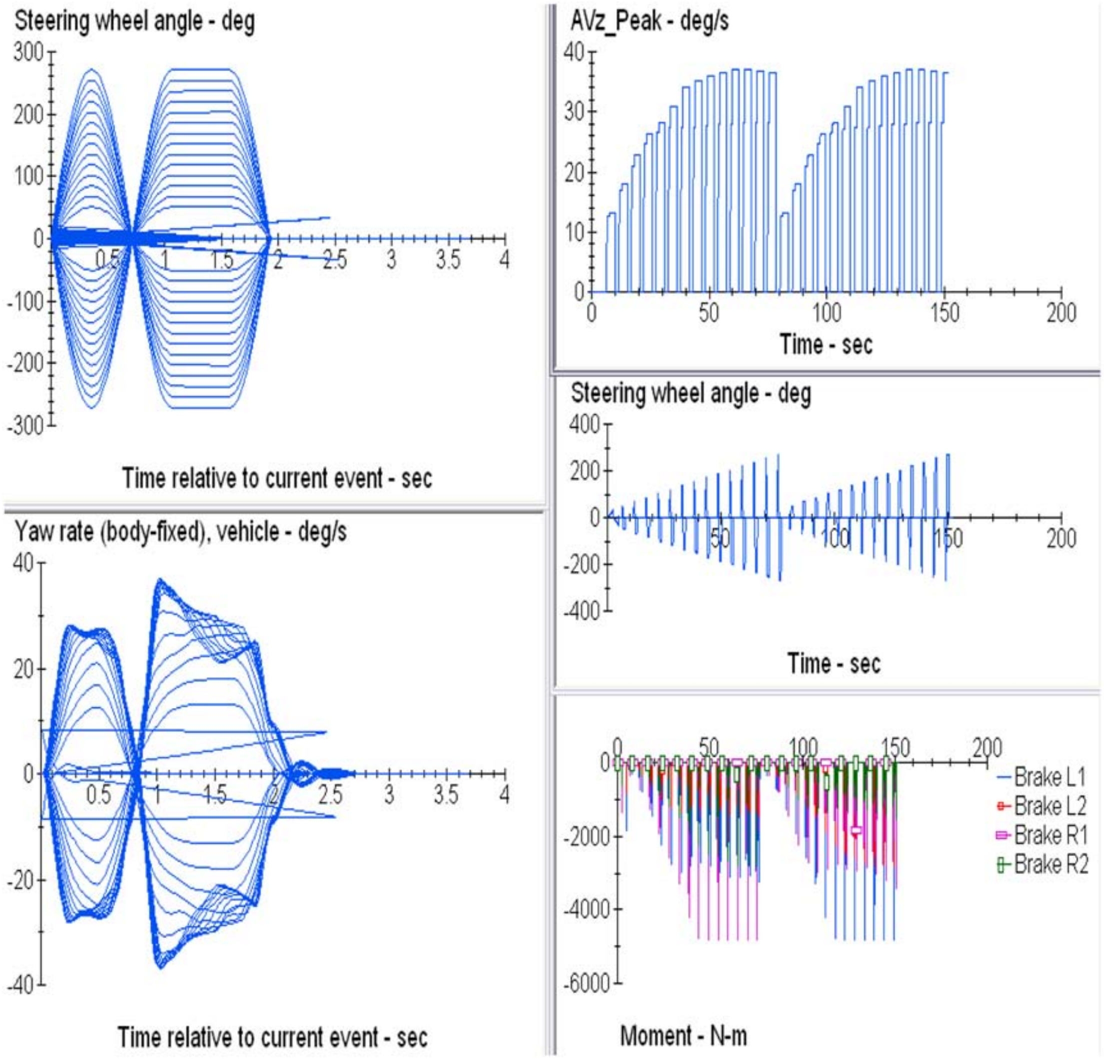

Figure 8. Response of the vehicle with ESC for the full test sequence

defined in Simulink. Using the controller, the vehicle passes the FMVSS 126; the same vehicle fails the test without the controller.

The example dataset in CarSim 7.1 uses a large SUV vehicle with a simple ESC controller defined in Simulink to use the brakes when needed to maintain stability.

Figure 8 shows some plots made from the simulation. The two on the left side show responses as functions of local time, with the appearance of many repeated tests. The others show responses as functions of absolute time." [6]

The process used for implementing the pure simulation approach requires knowledge of all key characteristics:

• Vehicle dynamics
• Tire characteristics
• Control algorithms and calibrations

Currently, that means the Aftermarket Manufacturers must:

• Test the production vehicle for kinematics and compliance (K&C data)

• Measure the tire characteristics at an appropriate facility

• Estimate or idealize the sensor and actuator response characteristics

• Implement generic control algorithms as representative of the capabilities of a given ESC system

Yet the OEMs and their Tier One suppliers have all that information available to them AND there are encryption protocols that would maintain the intellectual property of each subject while enabling enhanced fidelity of the overall pure simulation models. This, in turn, would enable the development of design envelopes for a given vehicle to maintain appropriate vehicle dynamics behavior while being customized to the satisfaction of the consumer.

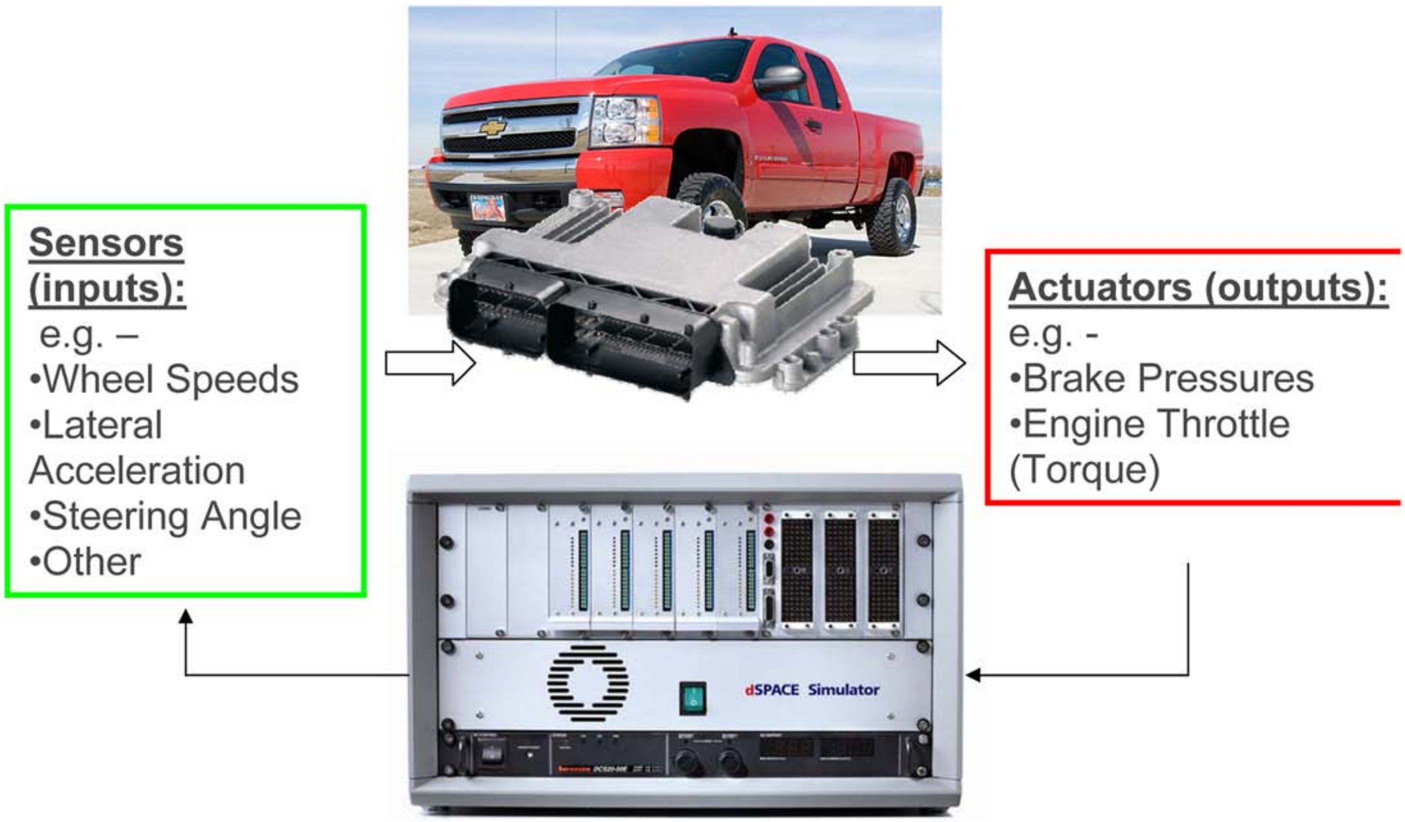

Figure 9. Simple diagram of HIL components

Hardware In the Loop (HIL)

The third approach this paper explores addresses some of the issues of the previous methods, yet comes with its own unique challenges. With the addition of the capabilities offered by dSPACE tools, true real time simulation can be achieved while interfacing with selected production vehicle hardware and systems.

In response to the implications of FMVSS 126, from both regulatory and litigation standpoints, SEMA has sought to provide its Aftermarket Members with knowledge and capabilities that would be difficult to obtain on an individual company basis. To that end, a simulation capability has been established through a vehicle dynamics software package (CarSim) and using its capabilities to mimic the FMVSS126 test procedures. However, in the pure simulation mode, and using a generic Electronic Stability Control (ESC) algorithm, this approach can demonstrate the potential for a modified vehicle to comply with the standard, but does not directly represent the given application.

In order to increase the degree of confidence in the simulation of a given vehicle's performance, it is proposed that SEMA facilitates the development of a flexible, collaborative Hardware In the Loop (HIL) capability to incorporate the actual ESC controller in the simulated performance evaluation and in a representative vehicle present to address all the communication and diagnostic complexities presented by current automotive electronic architectures.

The hardware components required for this proposal are shown below in Figure 9:

The vehicle measured only needs to be representative of the original vehicle before modification. The key elements are the actual ESC controller and the electrical architecture of the OEM vehicle. The vehicle modifications are handled by the parameters set in CarSim.

The HIL approach addresses the control algorithms and calibrations issue and the need for modeling sensors and actuators by using the actual systems in the simulation. In an effort to assist its members in demonstrating due diligence in meeting the requirements of FMVSS 126, the Specialty Equipment Market Association (SEMA) is developing a Hardware In the Loop (HIL) facility to evaluate the modifications its members make to production vehicles in a simulation environment. Using simulation tools provided by Mechanical Simulation (CarSim) and dSPACE, a static vehicle is connected to the hardware to determine how its electronic controllers respond to the simulated test maneuvers with its modified vehicle characteristics.

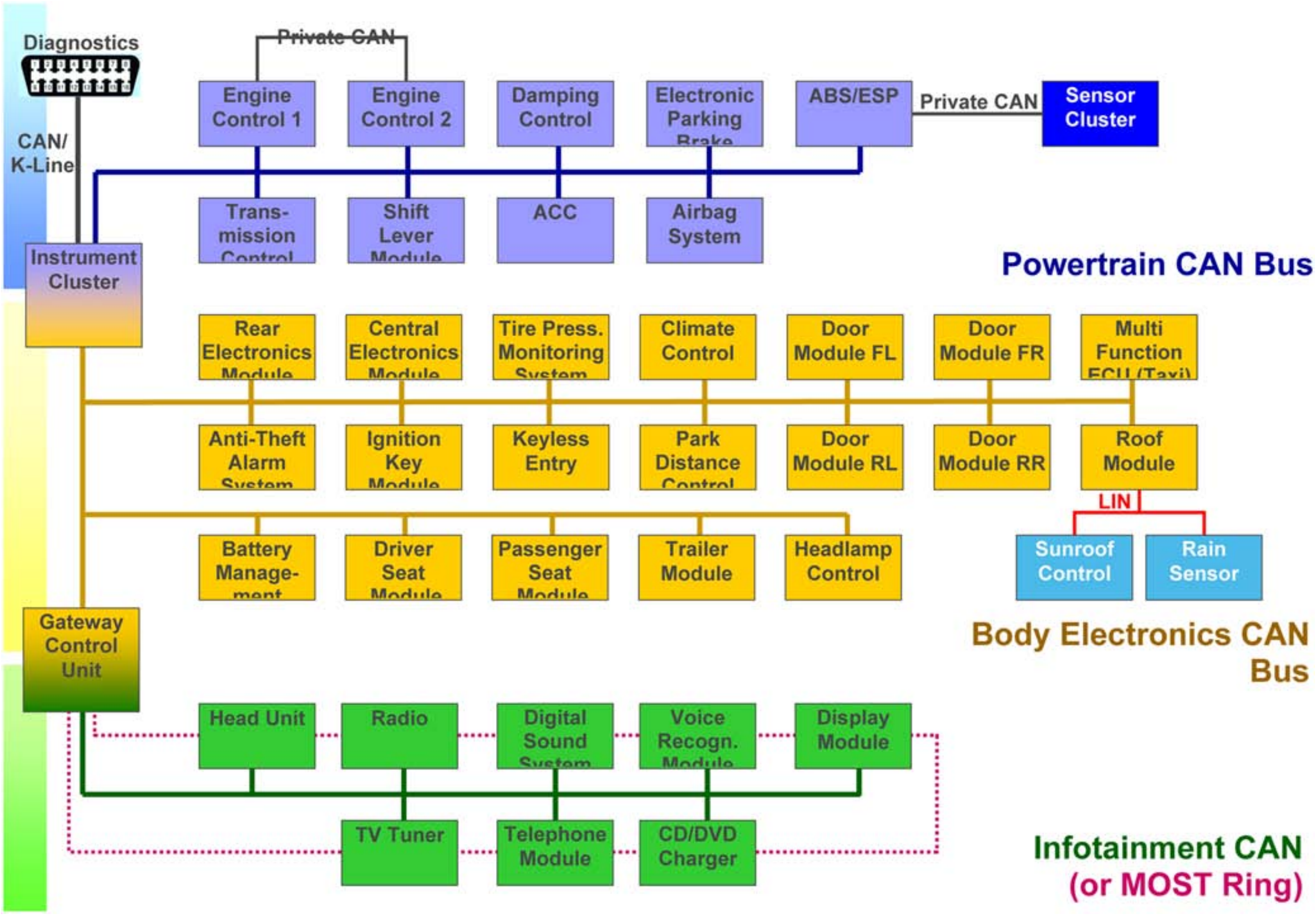

Figure 10. The Brains: Networked Electronic Control Units

By using this approach, SEMA and its members do not need to delve into the intellectual property contained within the controllers. The algorithms and calibrations established between the Original Equipment Manufacturer (OEM) and its chosen Tier One Supplier remain confidential, respecting their proprietary nature. Every controller on the vehicle is treated on a "signals in, signals out" basis.

In order to achieve this capability, three sets of data need to be defined:

1. Kinematics and Compliance - This data involves the static parameters of the vehicle and the dynamic aspects of its steering and suspension systems. Measurements of characteristics such as center of gravity, roll, pitch, and yaw inertias, as well as frame torsional flexibility are all used to describe a specific vehicle.

2. Tire Data - Since the forces developed at the tire road interfaces are critical to a vehicle's dynamics, measures of a tire's characteristics are paramount in establishing a meaningful simulation. Effective rolling radius, rolling resistance, and spring rate are some of the other parameters required.

3. Signal Composition - The nature of sensor information is key to being able to simulate accurately. Directly wired sensors are readily mimicked, but serial communication based sensors take time to decipher. Knowing the protocol for information transfer enables the simulation techniques to be employed.

As stated before, we believe an HIL facility offers OEMs, Tier One Suppliers, and Aftermarket Manufacturers unprecedented means of providing an innovative and mutually beneficial technical exchange. The unique support and information provided by this approach would be difficult, if not impossible, for companies to obtain individually at this level of confidence and efficiency.

Conclusions

The technical challenges the Aftermarket Manufacturers and Simulation Tool suppliers face in working with OEMs and Tier One suppliers are well understood. Understanding the complex electronic architectures as shown in Figure 10 present hurdles, but is certainly doable with the appropriate amount of information sharing.

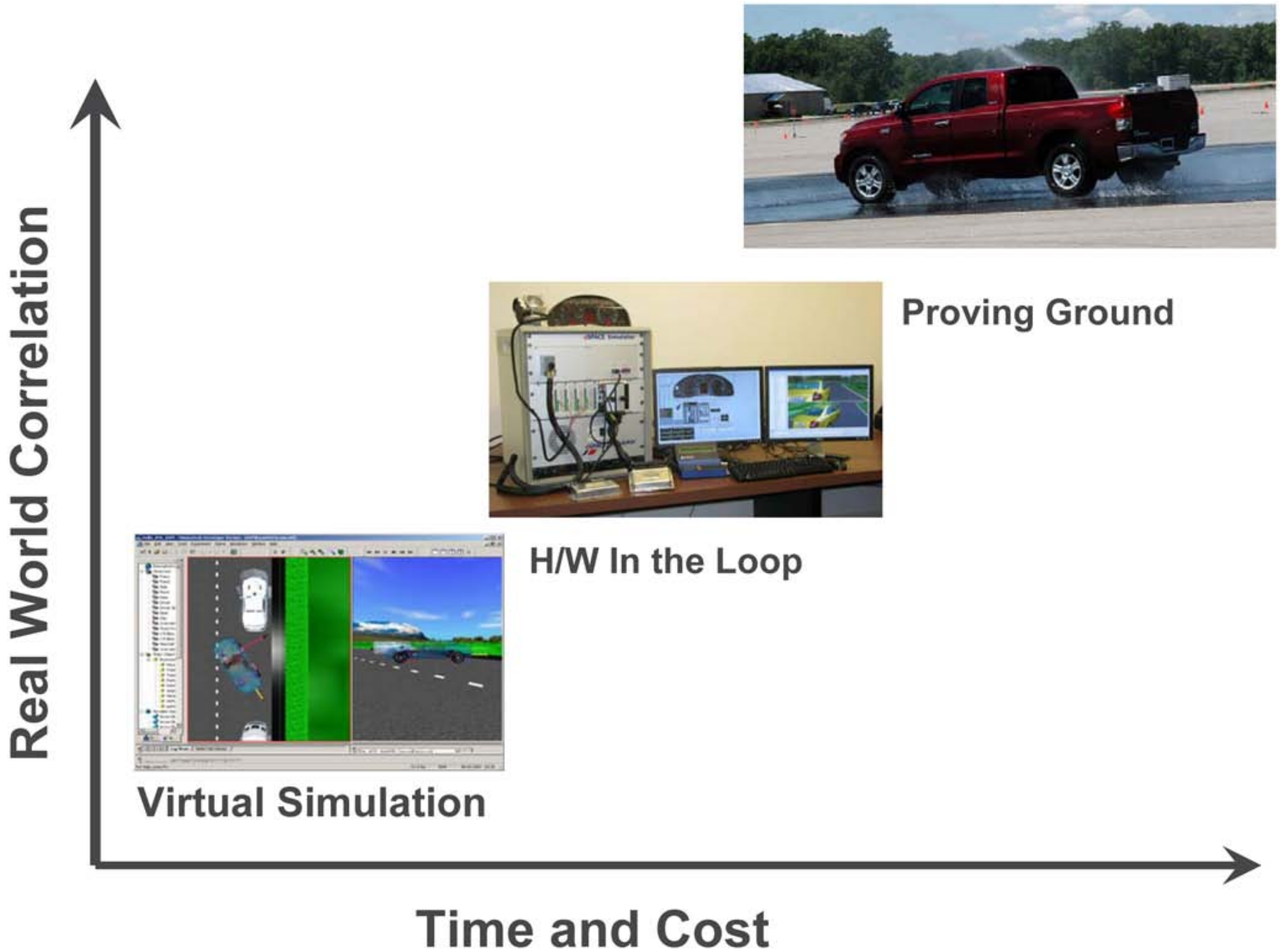

Figure 11. Objective Trade-offs

The measures for deciding which projects are worth pursuing and of value to a given program are also well documented, as summarized in Figure 11 below.

The challenges the Aftermarket Manufacturers and Simulation Tool suppliers face in ***collaborating*** with OEMs and Tier One suppliers are:

• respecting the intellectual property of OEMs and Tier One suppliers

• maintaining the integrity of individual Non-Disclosure Agreements (NDAs) in cross-collaborative efforts

• providing a sustainable mutually beneficial business model

• establish involvement with tire companies

◦ sponsor/provide tire data for database

◦ demonstrate viability for application in accordance with FMVSS 126

• establish relationships with OEMs and Tier One suppliers

◦ enable restricted access to serial data

◦ demonstrate accessibility for customization (desirability factor)

◦ provide a complete functional demonstration with data available for critical review

It is clear, as shown in Figure 12, that the technology is readily available to enable unprecedented mutually beneficial collaboration among companies that traditionally only competed with each other or operated purely at “arm's length”.

Figure 12. HIL: A Collaborative Value Proposition

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