IDEA

Innovations Deserving
Exploratory Analysis Programs

Safety IDEA Program

Driver Alertness Indication System (DAISY)

Final Report for
Safety IDEA Project 07

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November 2006

TRANSPORTATION RESEARCH BOARD
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Safety Innovations Deserving Exploratory Analysis (IDEA) Program Managed by the Transportation Research Board

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1. EXECUTIVE SUMMARY

The objective of this project is to test and demonstrate the innovative concept for detecting driver inattentiveness that was developed by Sphericon. This approach is based on the fact that the on-going activity of the driver is to maintain the vehicle within the lane while external forces – due to bumps and imperfections in the pavement, air gusts from winds and passing vehicles, imbalances in the vehicle itself, and the like – continuously attempt to move the vehicle away from its intended path. The balance between these two factors, driver activity (DRA) and disturbances activity (DSA), reflects the level of driver alertness.

Sphericon’s approach utilizes a two-step method: (1) the extraction, separately, of DRA and DSA from the dynamics of the steering system, and (2) the use of digital signal processing (DSP) algorithms to detect driver inattentiveness from the two outputs of step one. Driver input and disturbances input can be resolved by simultaneous measurements of steering wheel motion and road wheel motion. Sphericon's product DAISY (driver alertness indication system) will performs these measurements and run the algorithms to compute the Alertness Index. It will then issue a signal when the alertness of the driver is determined to be below a preset level.

This project was the third step in the validation of the DAISY concept. The objectives of the two preceding steps were, respectively, (1) to confirm that the dynamic parameters of the steering system could be measured in the driven vehicle environment and that they were relevant to the separation and the assessment of DRA and DSA, and (2) to demonstrate an algorithm that determines the level of driver alertness (“Alertness Index”) on the basis of known DRA and DSA values. The two first steps were completed successfully. The final laboratory-level validation, which combines the two steps and applies them on a real, physical steering system, was the subject of the present project.

A major task of the project was the development and construction of a hybrid (hardware-in-the-loop) simulator which integrated a real steering system with a computerized simulator and with an elaborate set of sensors and data acquisition system. It also involved the construction of a computer controlled load generator which provided the appropriate load on the steering system in accordance with the instant dynamics of the virtual vehicle. This way, the dynamic behavior of the steering system was maintained equal to that of an identical steering system installed in a real vehicle performing the same maneuvers. The use of such a simulator is a must in order to allow experiments with inattentive drivers in the safe environment of the laboratory. The development and satisfactory completion of the simulator proved to be more time consuming than anticipated but eventually all difficulties were removed and a positive validation of the simulator performance was achieved.

The last stage of the project included the enhancement and verification of the DAISY algorithms. This involved conducting driving tests in the hybrid simulator with drivers at different stages of alertness and analysis. Two approaches for the extraction of DRA and DSA, involving two different methods for performing the necessary measurements, were examined, involving different dynamic parameters of the steering system. One method turned out to be easier to analyze and more practical for implementation and consequently was selected for the analyses of the tests results.

Twenty-four tests were conducted of which eight were discarded due to various problems with the use of the new simulator system or with the test subjects. Analyses of the data were performed and the algorithms were enhanced to conform to the selected measurement approach. The results obtained from the tests were translated into an alertness indicator which was then compared with an index produced by subjective judgment: two investigators observed independently the recorded video of the test subjects and graded their level of alertness.

The comparative analyses made resulted in rather promising results. Although still qualitative in nature, due to the lack of a quantitative criterion for comparison at that stage, the similarity of the pattern of the alertness index generated by DAISY to that produced by the subjective judgment method indicated the validity of the principles that govern the operation of DAISY.

2. THE PRODUCT

2.1 THE DAISY SYSTEM

Sphericon's DAISY (driver alertness indication system) is intended to address the problem of driver inattentiveness. Drivers become inattentive due to fatigue, the use of alcohol or drugs, or distraction and preoccupation. DAISY will detect the level of alertness of the driver and will warn him/her when it is down to dangerous levels.

The system is, basically, "software on a chip" product made for integration with the vehicle steering system. Figure 1 depicts a schematic description of the integration of DAISY with a steering system. DAISY will receive information on the steering system dynamics from two sensors located, respectively, at the steering wheel side and at the road wheel side of the steering system and from the vehicle speedometer. DAISY will communicate with the vehicle computer and will send it a signal when the warning of the driver is necessary.

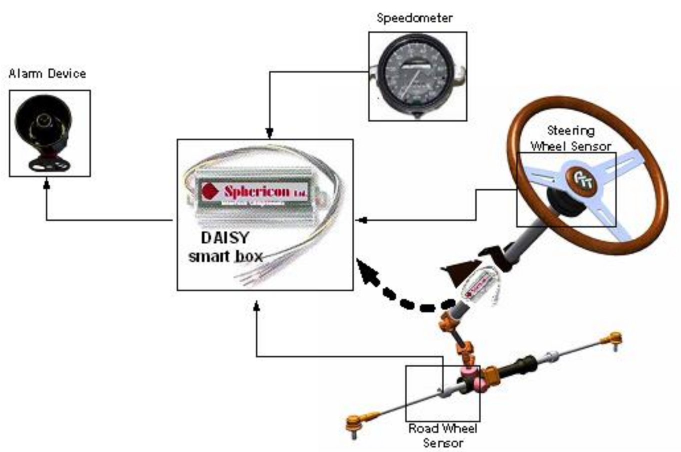

Figure 1: DAISY integration with a steering system

2.2 PRODUCT PROLIFERATION

DAISY is presently being developed for installation in new vehicles during production. The possibility of its expansion into the after-market will be explored, in particular for heavy vehicles where installation and interfacing with existing vehicle is likely to be considerably easier.

The first users of DAISY are expected to be the long-haul trucking and motor coaches, large fleet companies. Their operations are typified by long driving hours, and they suffer the most when a company vehicle gets involved in a fatigued and drowsy driver related crashes. Moreover, the decision to use a driver monitoring and alarm system is made by management, not by an individual driver who might not be keen on putting a safety device high on his or her priority list. Other commercial vehicle companies are expected to follow suit, motivated by the apparent performance of the system.

The penetration of DAISY into the passenger car market is expected to start at the high-end, car models. This is the market segment where new features are usually tested first due to the relatively large profit margins which give the car manufacturer the freedom to try new features and because the typical luxury car users are inclined to try new technologies in their cars. The installation of DAISY will then expand into other passenger vehicles models, as has been the case with other active safety systems in recent years.

Following the proven impact of DAISY (and, perhaps, other similar systems) it is expected that the usage of DAISY will be encouraged, and gradually become mandatory, in many countries and states.

2.3 IMPACT

The magnitude of the problem of inattentive drivers is well recognized in the United States and around the world. The best testimony to that effect is summed up, perhaps, by the following quotations:

Drowsy driving causes more than 100,000 crashes a year, resulting in 40,000 injuries and 1,550 deaths… It is widely recognized that drowsy driving is underreported as a cause of crashes. And this doesn't include incidents caused by driver inattention.
— U.S. National Highway Traffic Safety Administration (NHTSA)

The cost of drowsy driving—diminished productivity and property damage—is estimated to be $12.5 billion annually in the United States.
— National Sleep Foundation

Fatal-to-the-driver heavy truck accidents… probable cause was fatigue (31 percent) followed by alcohol and other drug use impairment (29 percent).
— U.S. National Transportation Safety Board (NTSB)

There were 16,653 alcohol-related fatalities which accounted for 40% of total traffic fatalities in 2000.
— National Center for Statistics & Analysis

Driver distraction is perhaps the most demanding highway traffic safety issue of the day…
— Rosalyn G. Millman, Deputy Administrator, National Highway Traffic Safety Administration

In view of the great role inattentiveness takes in automotive accidents, the impact of DAISY on transportation practice, both from economic and humane stand points, is obvious and needs not any further elaboration.

3. CONCEPT AND INNOVATION

Over the past thirty years, researchers and engineers seeking solutions to the problem of inattentive drivers have suggested many methods to determine driver competency. These have included using sensors to monitor physiological parameters of the driver; tracking eye closure and blinking characteristics; attempting to correlate steering wheel motion and throttle pedal motion with degree of alertness; and active methods requiring driver response to some visual or audio stimuli. None of these methods have provided a feasible, cost-effective, marketable solution. Drivers are averse to mounting sensors on their bodies or having to contend with "nagging" monitoring devices. Eye tracking, which had shown promising results in the laboratory, encountered numerous problems in real-world use due to drivers' changing their body positions or wearing eye- or sunglasses. Steering wheel and pedal motion analysis results are ambiguous. Lane departure warning systems, based on cameras to determine the position of the vehicle with respect to lane boundaries, have recently become available in some car and truck models. While unintended lane departure is related to inattentiveness, it is not the only manifestation of inattentiveness and it is an after the fact event. Also determination of the vehicle position in the lane requires substantial infrastructure investment and is hindered by snow, wet surfaces, and the like.

None of these flaws are relevant to Sphericon's DAISY. DAISY does not test the driver. It tests the driving, and therefore is universally applicable to any cause of inattentiveness — fatigue, drugs, or alcohol — and is not limited to any one cause.

The essence of driving is controlling the lateral position of the vehicle. One would naturally expect that analyzing the motion of the steering wheel would provide a good indication as to the driver's state of attentiveness. Indeed, many researchers tried this approach. But they all failed because the results did not provide a sufficient level of certainty. A closer look at the driving process gives an explanation to that consistent ambiguity. In fact, there are two "players" involved in the driving process: one is the driver who uses the steering wheel to maintain the vehicle within the lane boundaries; the other is "the external world"— bumps and imperfections in the pavement, air gusts from winds and passing vehicles, and imbalances in the vehicle itself — that continuously attempt to move the vehicle away from its intended path. The significance of the second player, the disturbances, is easy to confirm: when the driver's hands are removed from the steering wheel, it is often only a matter of seconds, on the best of roads and under the best conditions, before the vehicle starts to veer off the road. Trying to determine driver alertness from steering patterns alone — without regard to external forces — is therefore bound to yield ambiguous results.

The situation changes dramatically when data extracted from the steering system dynamics are both the driver's intended steering action **and** the action of the disturbances induced by the external world. Sphericon's method provides this information. High-rate, high-resolution measurements of the steering system dynamics and algorithms utilizing digital signal processing (DSP) methods have enabled Sphericon to identify the accumulated action of the external forces as they disturb the motion of the vehicle along its path separately from the action of the driver who acts to maintain the vehicle on the road. Analysis of the driving pattern vis-à-vis the pattern of the disturbances allows a continuous determination of the driver's level of alertness.

The ability to determine each, driver action (DRA) and disturbances action (DSA), from measurements of the steering system dynamics stem from the fact that DRA and DSA are originated at the upper end (near the steering wheel) and the lower ends (near the road wheels), respectively. A motion initiated by the driver originates at the steering wheel, and the motion of the road wheel lags somewhat behind. Conversely, a motion due to external disturbances starts at the road wheels and the steering wheel follows. Data measured simultaneously at both ends contain the information necessary to discriminate DRA from DSA.

DAISY, due to its unique method of operation, is anticipated to be insensitive to the type of vehicle driven or the age of the vehicles of the same general size. The differences between vehicles of various models or their mechanical state are expected to influence equally both – the disturbances entering the steering system and the response of the driver. In DAISY, the activity of the driver is weighed against the activity of disturbances. In the process, the effect of the disturbances is cancelled out, so to speak, and the net alertness of the driver is obtained.

4. INVESTIGATION

4.1 BACKGROUND

Sphericon had set a program to assess its innovative concept for detecting driver inattentiveness. Sphericon's approach utilizes a two-step method: (1) the extraction of both driver action and "external world" action (disturbances) from steering system dynamics, and (2) the use of digital signal processing (DSP) algorithms to detect driver inattentiveness from the two outputs of step one.

Figure 2: Sphericon's test truck

Sphericon's concept validation program was divided into three phases of which the current project is the final one. The objectives of the two initial phases were, respectively, (1) to confirm that the dynamic parameters of the steering system could be measured in the driven vehicle environment and that they were relevant to the separation and the assessment of DRA and DSA, and (2) to demonstrate an algorithm that determines the level of driver alertness ("Alertness Index") on the basis of known DRA and DSA values. These phases were completed successfully.

For the sake of completeness, two examples of results obtained in tests made during the initial two phases of the concept validation are briefly discussed.

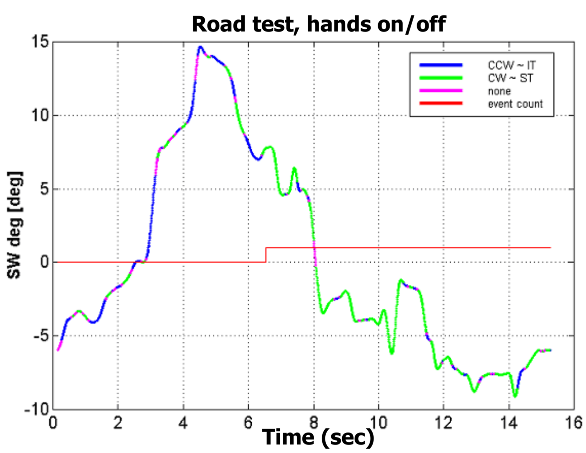

Figure 3: Previous results – measurability and separability of DSA and DRA

4.1.1 Results of previous work - Phase 1

An MAN truck trailer (see Figure 2) was used in the initial phase to validate the measurability of the pertinent parameters for the assessment of DRA and DSA. The truck was equipped with various sensors that measured the dynamic behavior of the steering system and was driven on roads of various qualities. Algorithms were applied off-line on the recorded data to determine, qualitatively at that point, the activity of the driver in comparison to the activity of the disturbances. Figure 3 demonstrates the results in a particular, illustrative test. It shows the mapping of the steering wheel angle over time. The curve is indicated in blue at points where DRA-dominated motion occurred at any particular instant and in green when DSA-dominated motion was detected. The middle, horizontal red line is the event marker, made to step up by 1 whenever the test operator manually pushed a button. This allowed the logging of particular events during the test. In this particular test segment an alert driver was driving on a paved road maneuvering the vehicle. At the specific point indicated by the stepping up of the event marker, the driver was instructed to take his hands completely off the steering wheel. The shift of the curve from predominantly blue to mostly green at the point of transfer from a driver-controlled steering system to a non-driver-controlled steering system, is clearly apparent.

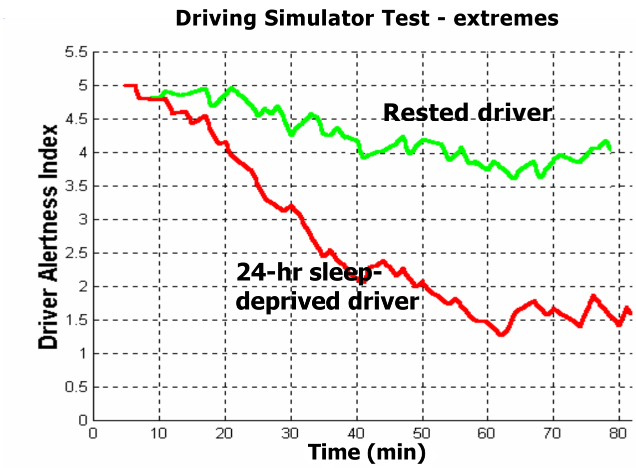

Figure 4: Previous results - Alertness Index vs. time of driver when rested and when drowsy

4.1.2 Results of previous work - Phase 2

In the second phase, a correlation between an Alertness Index, which is dependent on DRA and DSA, and the driver's state of alertness, was shown. Tests were carried out at Sphericon's virtual vehicle (as opposed to hybrid) driving simulator. The simulator, developed by System Technologies Inc. (STI) of Hawthorne, California, was equipped with a spring-centered steering wheel with no force feedback from the simulated vehicle dynamics. Thus the measured motion of the steering wheel provided the pure action of the driver (DRA). The driver's input signal was modulated numerically by prescribed disturbances (DSA) that were tuned to create a realistic response of the vehicle without being noticeable visually by the driver. The prescribed DSA and the measured DRA, as well as the vehicle speed, were used as inputs to the Alertness Index algorithm developed by Sphericon. The particular example shown here (Figure 4) is taken from driving tests with drivers in both extreme cases – fully awake or very sleepy. The subjects were university students who worked night shifts as security guards. Each test had two parts: one when the subject was fully alert, just before the beginning of his or her night shift; and another, when the driver was tired and drowsy after completing twelve hours of work. Typical results of such a test are given in Figure 4. The two curves each correspond to about one hour of driving through the same scenario in either part of the test: The line marked "Rested driver" is the evening session (before the start of the shift) and the line designated "24-hr sleep deprived driver" is the morning session (at the end of the shift). It can be seen that at the beginning of both sessions the alertness indexes have high values which indicate the driver's alert state. The post night shift curve, however, soon descends to low values, which correspond to a state of inattentiveness.

4.1.3 The Safety IDEA project

The final validation phase, in which the entire process is demonstrated, namely the measurement of the dynamics of a steering system under real driving conditions, the extraction of DRA and DSA and the determination of the driver alertness index, is the subject of the present Safety IDEA project.

A hybrid simulator (Figure 5) that combines a driving simulator with steering system hardware ("hardware in the loop") was constructed to satisfy the requirements of the laboratory tests. The hybrid simulator serves two purposes: (1) It is a development and verification tool for the DAISY algorithms, and (2) it provides a test bench for evaluation of the relevant dynamic parameters of steering systems for which DAISY will be adapted. These parameters will then be embedded in the algorithms of DAISY.

The use of a real steering system within the driving simulator required the construction of "the load generator" – a device that loads the steering system in the same manner that a vehicle's wheels would under the same driving conditions. The design and construction of the load generator was a critical part of this project.

Figure 5: Sphericon's hybrid simulator

4.2 SCOPE OF WORK

This project was planned to be performed in three stages. *Test Setup Design*, *Test Setup Development*, *Simulator Tests, and Concept Validation and Final Report*.

Stage I, *Test Setup Design*, included a system level design of the hybrid simulator and a preliminary design of the load generator and the structural platform on which the steering system and the load generator are integrated.

Stage II, *Test Setup Development*, included the detailed design and the construction of the load generator and the simulator structure, adaptation of the existing, fixed base simulator (hardware and software) for the hybrid simulator system, hardware and software integration of the simulator, and verification tests and analysis of the hybrid simulator functionality.

Stage III, *Simulator Tests, Concept Validation and Final Report*, was the final stage. Its purpose was to verify the ability to separate and quantify DRA and DSA and to assess their usefulness in the DAISY alertness index algorithms. It included the determination of the pertinent parameters of the selected steering system operating the hybrid simulator as a test-bench, carrying out simulator tests with subjects driving to the point fatigue and drowsiness, and the analysis of the recorded data to test the DAISY algorithms and to assess their applicability.

4.3 HYBRID SIMULATOR SYSTEM CONSTRUCTION

A major portion of this project was the design and construction of Sphericon's hybrid simulator. It included the integration of its fixed-base driving simulator with a complete steering system assembly, from the steering wheel down to the joint that connects to the rack with the road wheel's tie rod. Figure 6 displays a schematic diagram of the hybrid simulator design. The **Driving Simulator** is a PC based simulator, made by Systems Technology Inc. (STI) of Hawthorne, California. It is a three-degrees-of-freedom (3-dof) simulator that receives analog signals from the **Driver Controls,** namely the steering wheel angle, the brake pedal position and the accelerator pedal position, and calculates the kinematical parameters of the vehicle in longitudinal and lateral translation and in yaw. Accordingly, it displays the driver's forward view of the road, the scenery of which is pre-programmed and controlled by the user. The driver compartment of the hybrid simulator is situated in a body of a scrapped car, providing a real car-like environment for the driver. The steering wheel and the brake and accelerator pedals of the car replace the desktop and under-the-desk driver controls of the original STI simulator. The hardware-in-the-loop part of the hybrid simulator is the **steering system**. The simulator design provides for the integration of various steering systems, for the purpose of incorporating DAISY in different vehicle models. The steering system is controlled by the driver who applies steering torque on it by turning the steering wheel. On the rack side, in lieu of wheels, the steering system operates against the **load generator** which, in turn, emulates the appropriate forces resulting from the road wheels' aligning torque and external disturbances, and exerts them back on the steering system. The load generator action is determined by the **vehicle dynamics simulator,** which receives the instant kinematic parameters of the vehicle from the driving simulator and instructs the load generator as to what force to provide. A detailed, more elaborate block diagram of the hybrid simulator is shown in Figure 7. It includes the building blocks of each of the hardware components in the simulator and the variety of sensors to be utilized. In addition, the interface to the DAISY system is shown. Note that for clarity, the interfaces of the sensors are described in the diagram according to their functionality. Physically, the sensors' signals are all channeled through signal conditioning units and a data acquisition system, not shown in Figure 7. The detailed information is provided in the sections that follow.

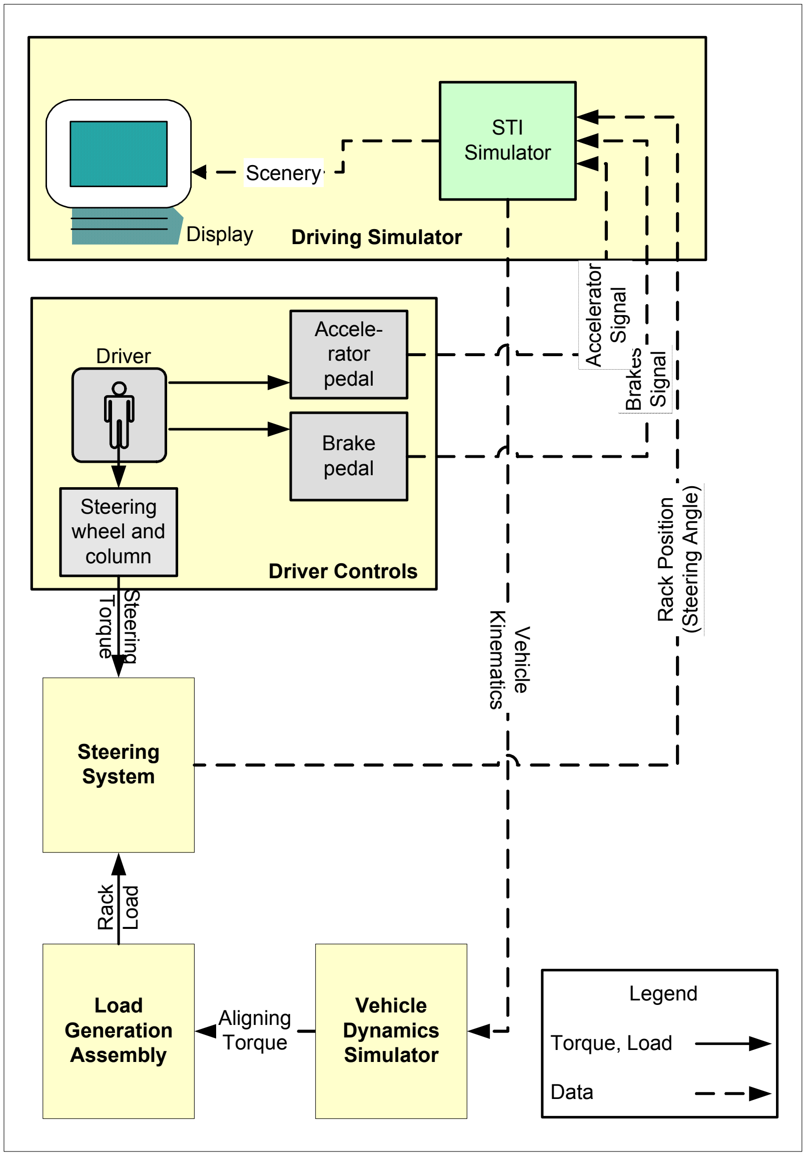

Figure 6: Sphericon's hybrid simulator architecture diagram

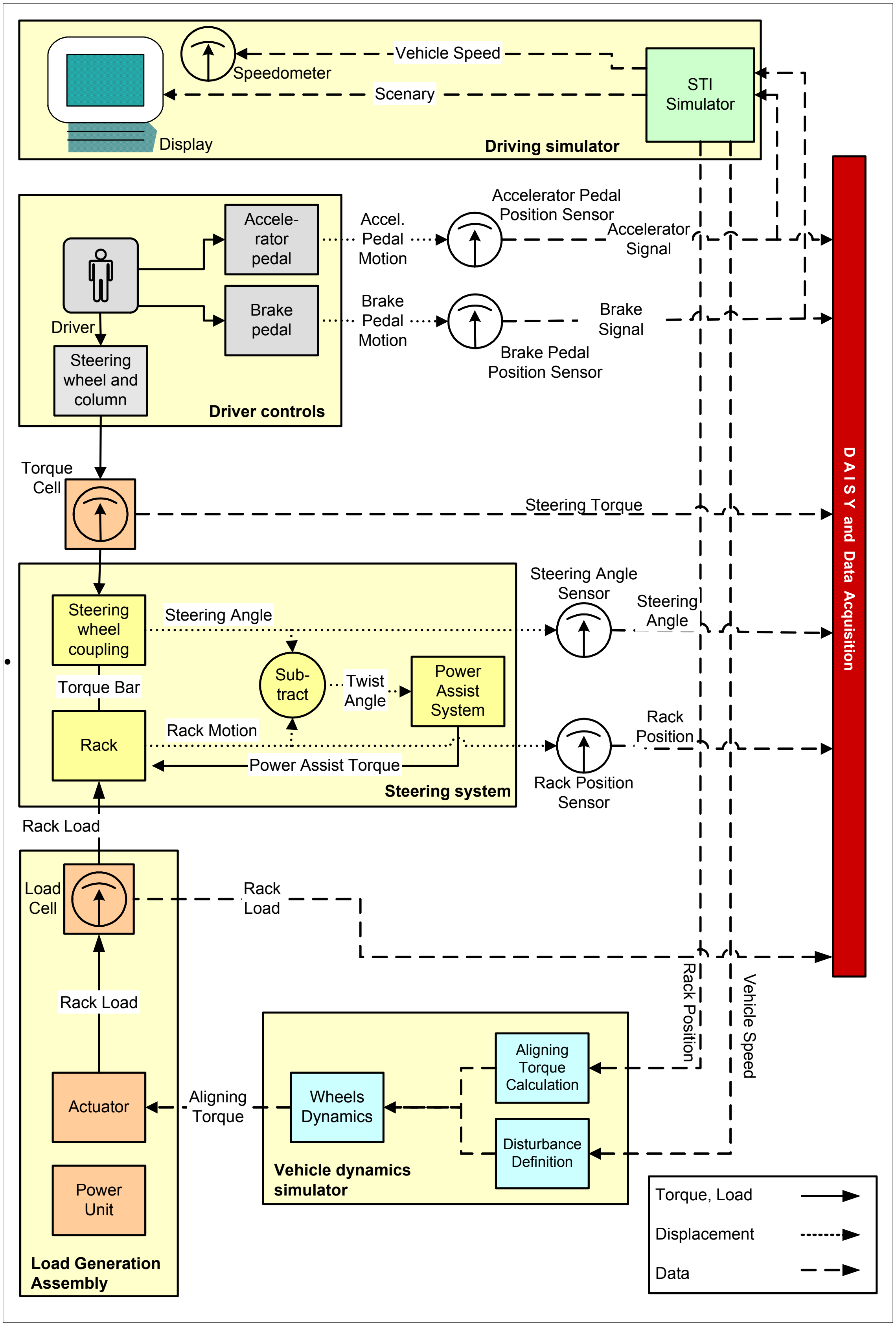

Figure 7: Hybrid simulator detailed diagram with instrumentation and DAISY integration

4.3.1 Hybrid Simulator Structure

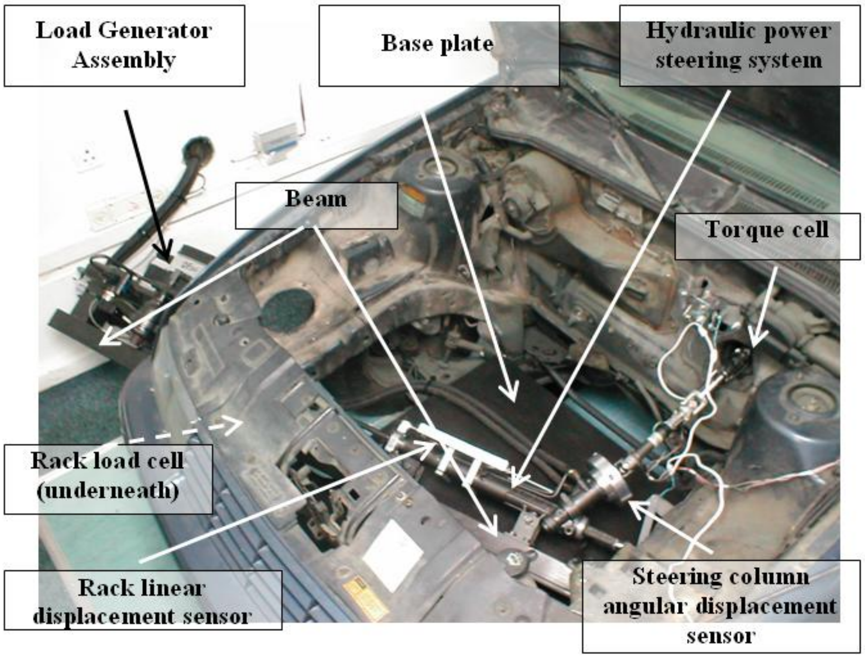

Figure 8: Steering system assembly in the hybrid simulator

The structure of the hybrid simulator was created in a scrapped GM Corsica structure (Figure 5). The rear part of the Corsica was cut and removed and its engine compartment was emptied of all the original parts of the vehicle. A metal plate was welded to the chassis in the emptied engine compartment (Figure 8) creating a rigid floor. This would be the base on which various steering systems of intended test vehicles would be installed for parameters evaluation and for algorithms design and verification. A rigid beam, mounted on the plate, provided the platform on which both the steering system and the load generator were installed, perfectly aligned and with no relative motion possible between them. The beam was oriented to allow appropriate mechanical integration of the steering system and the steering column of the simulator.

4.3.2 Steering System Integration

The steering system of an Oldsmobile Alero car* (a General Motors vehicle) was integrated in the simulator. This particular system was selected to match Sphericon's current test vehicle which is planned to be used for a demonstration of DAISY on General Motors' premises in 2007 (the demonstration program is outside the scope of this Safety IDEA program). The installed steering system operated within the simulator in a manner identical to its functioning in a vehicle and required no alteration relative to its operation. An external power unit provided the power assist system with hydraulic power according to the vehicle specifications.

The steering system, mounted on the carrying beam together with the load generator and installed in the simulator is shown in Figure 8. It is connected to the steering column of the simulator (the original Corsica unit) by means of an intermediate telescopic shaft, with a cardan joint on each side (a part of the Alero steering system) and a torque cell which measures the input moment applied by the driver. The end of the rack on the steering system's right hand-side is connected to the load generator through a load cell that measures the loads that are produced by the load generator to simulate the reaction forces and disturbances applied on the steering system by the wheels. Circular aluminum housing, attached to the steering system at the connection to the intermediate shaft, contains the rotary sensor which measures the angular displacement of the steering wheel. A rectangular box, mounted along the housing of the rack, contains the sensor that measures the rack linear motion.

4.3.3 Load Generator Design and Construction

Proper operation of the load generator is crucial for the performance of the hybrid simulator. The requirements imposed by DAISY dictate that the load generator is capable of producing a variable load covering a wide dynamic range, both in terms of magnitude and of frequency. LYA Ltd., a Tel Aviv company and Sphericon's subcontractor for

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* The MAN truck, which had been used for the initial phase of DAISY concept validation, was no longer available to the company for testing.

the construction of the hybrid simulator, carried out the load generator design and implementation. The load generator assembly consists of an actuator (Figure 9) and a power unit (Figure 10). The block diagram of the actuator is presented in Figure 11. It is comprised, essentially, of a hydraulic piston assembly (LYA), a servo valve with an amplifier (Parker), a load cell (Tedea Huntleigh) and a closed loop control unit (not shown in the photo) that operates the valve. The control unit communicates with the simulator computer from which it receives, in terms of voltage (V), instant load commands at a constant rate of50 Hz. The load cell measures the force produced by the hydraulic piston and provides the control unit with feedback on the measured load. The control unit regulates the valve, which controls the flow rate (Q) of the hydraulic fluid and thereby the pressure (p) in the two sides of the piston cylinder, and maintains the desired load on the steering system rack.

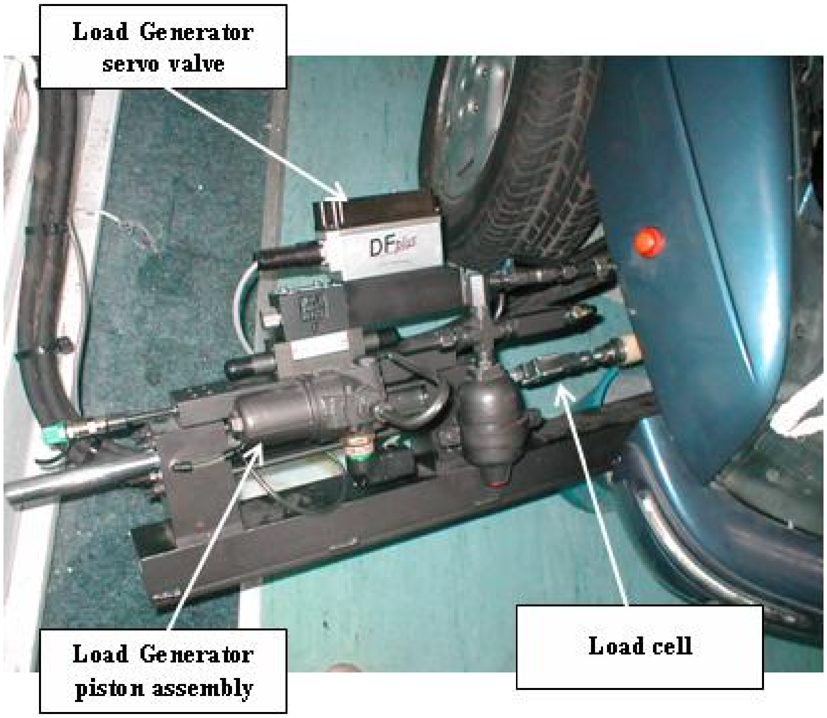

Figure 9: Load generator actuator assembly in the hybrid simulator

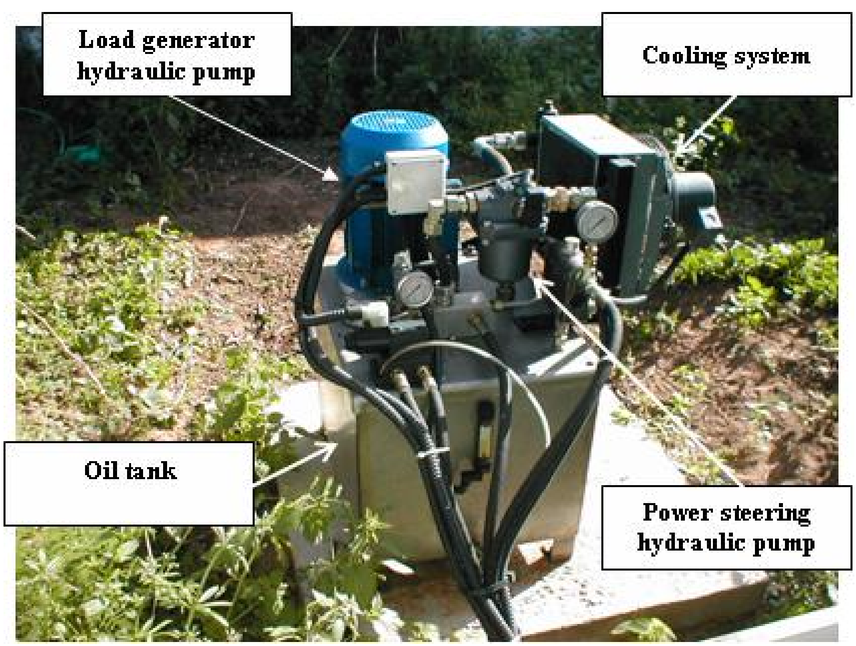

Figure 10: Hybrid simulator power unit

4.3.4 Power Unit

The dual power unit (Figure 10) employs two electric pumps that feed, independently, pressurized hydraulic fluid to the load generator and to the power steering system. The unit has been placed in the outside, at a short distance from the laboratory wall, to prevent its noise from disturbing the simulator tests. An opening has been made in the wall for the passage of the fluid tubes and electric cables. In addition to the pumps, the power unit contains a fluid tank, a cooling fan, pressure gages, a safety valve and switches.

4.3.5 Hybrid Simulator Instrumentation

The hybrid simulator test and measurement system includes the following basic elements:

- Sensors measuring the relevant physical data.
- Signal conditioning elements that provide an interface between the sensors and the data acquisition card.
- Data Acquisition card that samples the sensor signals (output of the signal conditioning elements).
- Synchronization elements, enabling synchronization of the sampled signals with other stored data, such as video recording and simulator events.
- Actuation elements, providing an interface between the simulator and other parts of the hybrid simulator.

4.3.5.1 Sensors

The various sensors that are employed in the hybrid simulator are shown in the system diagram, in Figure 7. Table 1 below details the function-ality of each sensor.

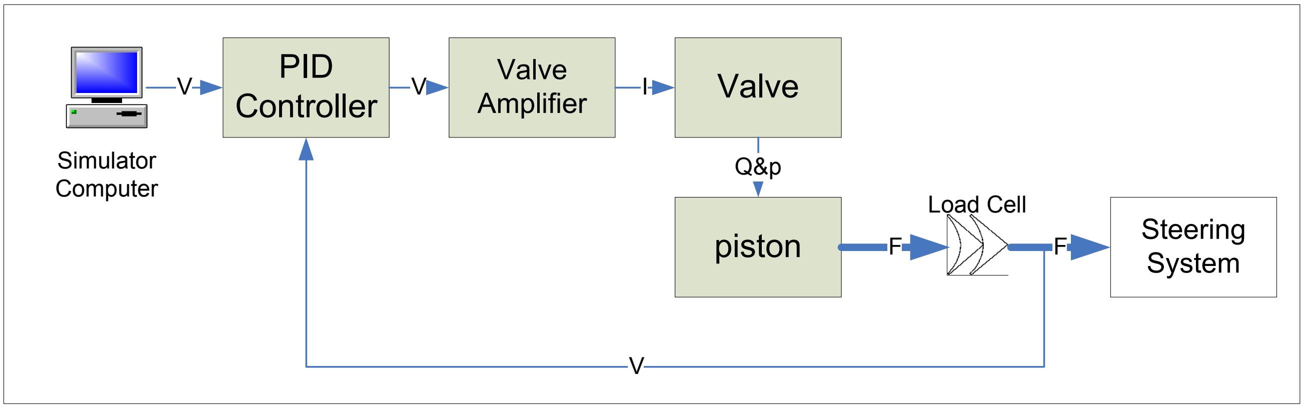

Figure 11: Load generator actuator block diagram

4.3.5.2 Signal Conditioning

4.3.5.2.1 Gage Bridge

The National Instruments full-bridge load cell signal conditioning module provides excitation and signal amplification for the torque cell and the load cell.

4.3.5.2.2 Encoders

The encoders' signal conditioning module provides an interface to the Netzer Precision rotary and linear encoders. The Quadrature Interface module converts the quadrature output signals of the encoders to analog signals (voltage) which are sampled by the data acquisition system. One voltage is 'high-resolution,' allowing high-precision detection of small motion. A second voltage is 'low-resolution,' providing the full range of the measurement.

Table 1: The hybrid simulator sensors

Sensor type	Sensor Make	Physical quantity	Function
Rotary encoder	Netzer Precision, Rotary Electric Encoder	Steering angle	DAISY input
Torque cell	Futek, Reaction Torque Sensor	Steering torque	Algorithms verification
Linear encoder	Netzer Precision, Linear Electric Encoder	Rack displacement (equivalent to road wheel angle)	DAISY input
Load cell	Vishay T-H, S-type Tension-Compression load cell	Rack load	Algorithms verification; load generation control
Potentiometer	Standard	Accelerator pedal displacement	Simulator input
Potentiometer	Standard	Brake pedal displacement	Simulator input
Potentiometer	Standard	Rack displacement	Simulator input

4.3.5.2.3 Potentiometers

Standard signal conditioning for the potentiometers has been employed.

4.3.6 Data Acquisition System

Figure 12: Data acquisition system and test computer

4.3.6.1 Hardware

The data acquisition (DAQ) system (Figure 12) includes a data acquisition card installed in a lap-top computer. Its main task is to sample all the sensor and synchronization signals. In addition, it is used for the generation of actuation signals and for real-time feedback on the test progress.

The National Instruments DAQ that has been selected outperforms the requirements of 12 analog input channels, 12 bit resolution, and a sampling rate of 1000 samples per second necessary for the planned tests. It features:

- PCMCIA interface to a lap-top PC
- 16-channels analog inputs (single-ended)
- 16-bit resolution of the analog inputs
- 200,000 samples/sec
- 8 digital I/O signals
- 2 analog output signals

The excess analog input and digital lines are used for the synchronization functions. The analog output lines can be used for actuation signals.

4.3.6.2 Software

The DAQ test software, defined in Stage I, was implemented and tested. It provides for the sampling of 12 channels at the rate of 1000 Hz and accumulation at least two hours of continuous data. To minimize the risk of loss of information, the data is stored and saved in multiple files.

The software also provides real time graphical and numerical information on the test progress and the sampled signals.

4.3.7 Synchronization

The DAQ system toggles one of its digital I/O lines as a time reference. The signal is recorded by other systems employed during the test – the simulator computer and video recording of the driver during simulator tests – as well as by one of the spare analog input channels of the DAQ system itself. The data will be used for synchronization between the systems and to indicate time of events such as the start of sampling and operator marks.

4.4 SIMULATOR VALIDATION TESTS

A GM Alero vehicle, with a steering system identical to the hybrid simulator's steering system and equipped with essentially the same sensors as in the simulator, was used to obtain the necessary vehicle and steering system dynamic parameters and, subsequently, to confirm the adaptation of the simulator for the Alero characteristics. The confirmation tests consisted of performing similar maneuverings in the car, on real roads, and i9n the simulator, on virtual roads, over a range of speeds and road curvatures. Adjustments to the response of the load generator in the simulator were made until a satisfactory match of the responses of both steering systems was achieved. The results of one such test is shown in Figure 13. It demonstrates the correspondence between the measured force applied by the load generator on the simulator's steering system and the measured total force applied by the test vehicle's two front wheels on its steering

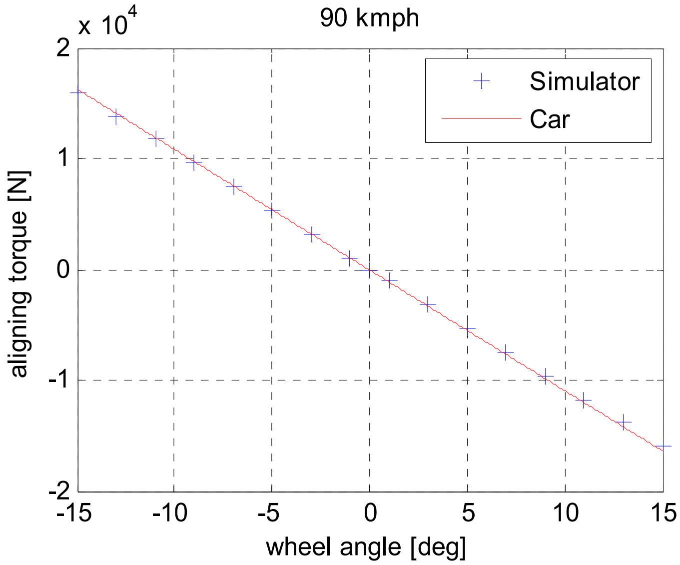

Figure 13: Simulator and test car comparison – load due to aligning torque at 90 km/h

system. The graph depicts, for a particular speed, the force in the vehicle (solid line) and the force in the simulator (dots) as a function of road wheels angle (right and left wheels averaged). In the range of road wheels angle which is of interest for this application, a variation between the two forces of less than 3% was achieved.

4.5 CONCEPT VALIDATION

4.5.1 Tests procedure

A preliminary set of about twelve tests were conducted with Sphericon team driving the simulator in wakeful state. These tests were used to examine the test procedures and to set the methodology for data analysis. A total of twenty four tests followed in two sets of twelve each. Test subjects were men and women in good health, in general in their mid-twenties to mid-thirties. Some flexibility was allowed in the age restrictions on the selection of the subjects as this was not considered a critical issue in the findings of this investigation. Drivers arrived around 10 p.m., filled out an information form and signed a short agreement. The information included items such as: how long they hadn't been asleep, how tired they were, their health situation (only people in general good health and with no sleep disorder could participate), etc. The agreement included their willing to participate and obey the rules, Sphericon's non-liability, and payment. Participants were paid by the hour, from arrival until departure. Their compensation consisted of two sums: the basic payment and a bonus. Traffic violations were subject to fines which could be deducted from the bonus (never imposed). After a short driving lesson on the simulator the drivers were served a meal. Actual driving tests started around 11 p.m. and were to last for up to five hours. The driving scenario used was rather boring, consisting of many straight and almost straight stretches of the road. Drivers were allowed one break after approximately two and a half continuous hours of driving. Tests terminated upon completion of five hours of driving or when drivers were completely exhausted. At the end of the test drivers were driven home. Of the twenty four tests, eight were discarded due to various problems involving drivers misbehaving or not feeling well (3),or technical problems with the computers or data acquisition (3), mechanical failure (1) and power outage (1).

4.5.2 Test data

Two computers accumulated data during the tests: the STI simulator computer (see Section 4.3) recorded data related to the vehicle performance, such as speed, distance, direction and traffic rules violations. The DAQ computer (see Section 4.3.6) stored information recorded from the various sensors that are installed on the steering system. Special events that occured during the tests were numbered, timed and recorded by the DAQ computer when the test operator hit a key on the computer keyboard. The operator then manually entered a description of the event in the test log. A video camera recorded the face of the test subject throughout the test. The road scene was also shown in the frame. The video was also displayed, during the test, on a monitor in the control room, allowing the operator to watch the test subject as well as the scenario. Upon completion of each test all the data were backed up and transferred for analysis.

4.5.3 Tests Analysis

The data analysis procedures involved several steps. The quantification of DRA and DSA was done by the following procedure:

- The separation algorithms were applied on the data from the steering system dynamics sensors to separate the disturbances information from the driver information
- High frequency information, which was irrelevant to human activity and was considered noise, was filtered out
- Low frequency information which was related to curvatures of the road was filtered out, virtually straightening the roads
- DRA and DSA were computed, respectively, from the two separated signals over short time periods, typically 20 seconds
- Alertness Index was computed as a relationship between DRA and DSA

4.5.4 Comparison with alternative methods

Proper validation of the experimental findings requires a comparison with available alternative methods. The method used in this project is termed by researchers "the subjective judgment method": an investigator observes the recorded video of the test subjects and grades their level of alertness subjectively. This method, widely used by investigators in drowsiness-related areas, had shown good qualitative results in tests conducted by Sphericon in the past.

The operators analyzing the video tapes were required to rely on the video recording alone and could not use the test logbook. Each tape was examined by two investigators who graded driver's alertness level from 1 to 5, 1 being widely alert and 5 meaning actually falling asleep. The subjective judgment was calculated by averaging the investigators' observation for each test. The agreement between the two subjective judgments was good as can be seen in the example shown in Figure 14.

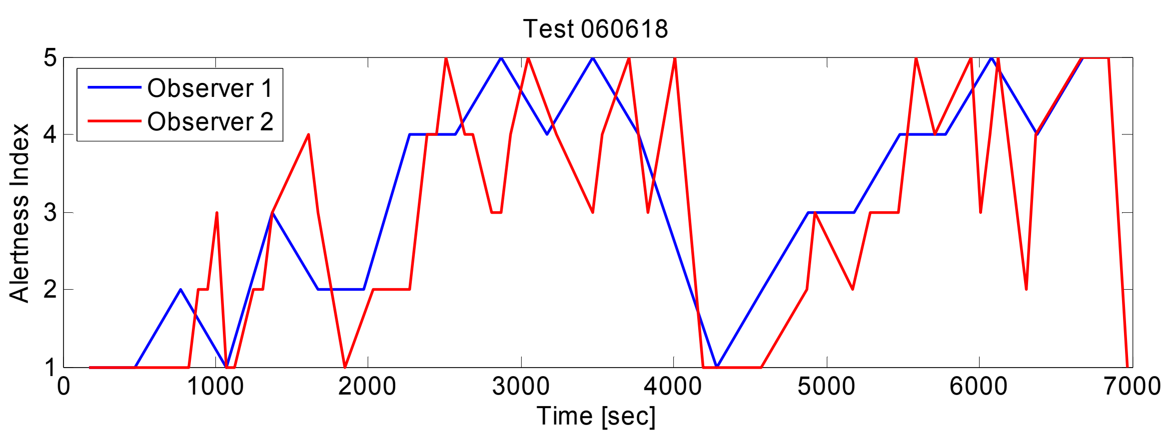

Figure 14: Comparison of two subjective judgments made by two observers of video recordings

Other alternative methods were considered by Sphericon but were found unsuitable:

- *Physiological parameters:* there is a debate among physiologists on how reliable are measurements of physiological parameters, such as EEG*, EMG**, and EOG***, in providing a quantitative indication on the level of drowsiness. Due to the great variability of physiological reaction among people, this approach would require

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*** Electroencephalogram, measured with electrodes glued to the test subject skin on the head**
**** Electromyogram, measured with electrodes glued to the test subject skin on the sides of the neck**
***** Electro-Oculogram, measured with electrodes glued to the test subject skin on the temples**

the recruit of a regular group of test subjects and their prior intensive testing in a sleep lab for the "mapping" of their relevant characteristics. Such effort was beyond the scope of this project and would be considered at the DAISY prototype development stage in the future.

- *Time to line crossing or time to collision:* the data of the number of times the vehicle comes close to hitting the lane markings or a neighboring vehicle is provided by the simulator but their application proved to be unsatisfactory and was abandoned.
- *Eye tracking:* this method required instrumentation unavailable to Sphericon and would be considered at the DAISY prototype development stage in the future.
- *Reaction time measurement:* This method requires the diversion of the driver's attention and, therefore, is not suitable for the method tested in this project which measures the attention the driver pays to the driving.

4.5.5 Concept validation results

The objective of this project was to demonstrate the concept developed by Sphericon to ascertain the level of driver alertness from a relationship between two physical quantities: DRA – the dynamic input a driver enters the steering system of a vehicle, and DSA – the input exerted by external forces through the vehicle's wheels. Agreement between the pattern of driver alertness as judged by subjective observers and the pattern derived from that relationship was considered a validation of the concept.

The calculated alertness values were normalized to fall between the values 1 and 5. Data from all the tests were used for the normalization that, subsequently, was unified.

A good qualitative agreement was found between the results obtained by applying the algorithms on the hybrid simulator tests data and the subjective judgment of video observers. Figure 15 presents the results of three typical tests, comparing the alertness index resulted by the two methods. In all these examples the agreement is obvious and cannot be incidental.

A point in case is the graph in Figure 15(c) in which test the driver was fully alert and singing throughout the test, showing some signs of tiredness only toward the end, after sunrise. The observers' assessment and the DAISY algorithms seem to be in full agreement.

In each of the tests shown, the driver was given a break. The breaks took place at different times: after 4,300 seconds driving in the first test (Figure 15(a)), after 11,000 seconds in the second (Figure 15(b)), and after 8,200 seconds in last test shown (Figure 15(c)). At the time of the break the calculated alertness index is meaningless and drops to the bottom. During the breaks data was not recorded so their durations are not shown.

Interestingly, the onset of fatigue determined by the algorithms seems to either match or trail behind the onset of fatigue as observed by the investigators watching the video. This is not unexpected as the appearance of the driver does not necessarily reflect exactly the driver's ability to control the vehicle. Clearly these phenomena will be subject to further investigation during the stages of prototype development in the future. Indeed, this supposition also explains the blue curve being at the level or below the level of the red curve.

The lack of a good quantitative criterion renders a thorough statistical analysis of the tests results inappropriate. Further tests, using quantitative criteria (e.g., PERCLOS), will be used in the following stages of DAISY prototype development.

4.6 INVESTIGATION CONCLUSIONS

In the course of the present project major achievements have been gained:

- A unique hybrid simulator, that integrates a fully operational hydraulic steering system made to function as if it was installed in a driving vehicle, was successfully constructed.
- Real disturbances were recorded in a driving vehicle, providing for the insertion of realistic disturbances in the simulator.
- Tests demonstrated the validation of the DAISY concept including:
    - Correct quantitative separation of DRA and DSA from measured steering dynamics
    - Derivation of alertness index that satisfactorily matches the pattern of alertness of the driver as assessed by observers' subjective judgment

The validation of the concept was confirmed.

(a)

(b)

(c)

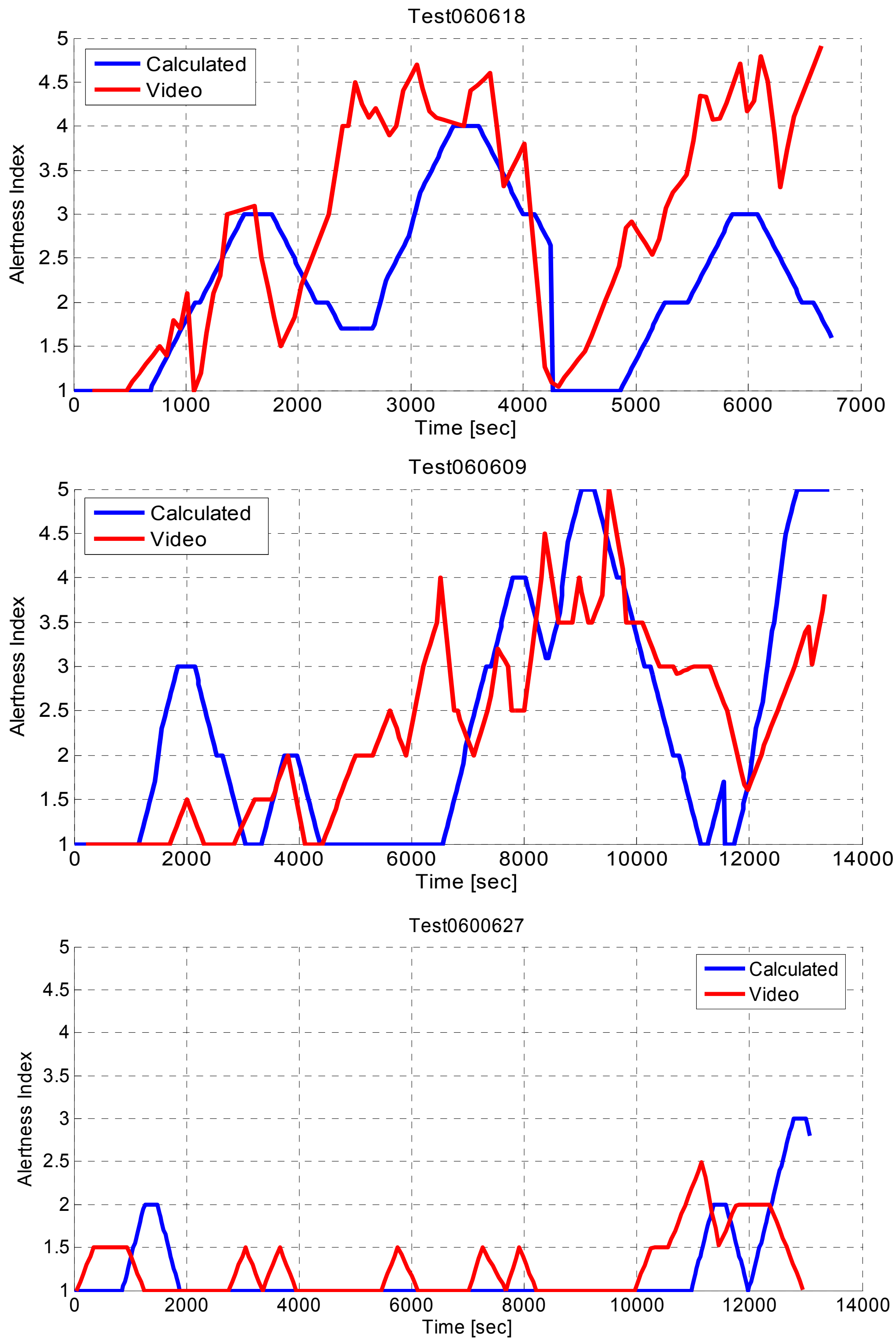

Figure 15: Calculated alertness index compared to an observer's subjective judgment

5. PLANS FOR IMPLEMENTATION

DAISY is intended primarily for installation in new vehicles. Its applicability for sales in the after-market is also being considered and seems likely, in particular for heavy vehicles such as long-haul trucks and motor coaches. The integration in new cars will be done in cooperation with the vehicle manufacturer and with the supplier of the steering system. In the design of the vehicle and the steering system provisions will be made for the installation of the DAISY "smart box" and the sensors. Some of the sensors, such as steering wheel angle may already be part of the vehicle design for other applications. DAISY will interface with the vehicle computer to receive pertinent inputs, such as the vehicle speed, and transmit the signal that alerting the driver is required.

After the completion of the product development Sphericon intends to manufacture and market it. Sphericon's customers will be Tier One suppliers who, in turn, will sell the systems to the vehicle manufacturers. The company will subcontract all mass production to companies with expertise in the automotive market and the manufacturing of electronic components and with the appropriate high volume manufacturing capability.

The automotive market is hard to penetrate. A great marketing effort has been made by Sphericon to bring DAISY to the attention of the vehicles manufacturers and the industry's major Tier One suppliers, primarily manufacturers of steering systems. The company is presently perusing a demonstration program with General Motors. The demonstration is due to take place in the second quarter of 2007 at GM's proving grounds in Milford, Michigan. Steering system manufacturers have shown great interest in the activity of Sphericon and will be willing to form commercial ties with the company when they receive indication from the OEMs on their intentions.

Customers demand has, perhaps, the greatest impact on the decision making processes in the automotive industry. This is particularly true for the big companies such as short- and long-haul companies, which have particular interest in reducing the involvement of their vehicles in crashes. Sphericon will work with these companies to influence truck manufacturers to include DAISY in the design of their vehicles and to explore after-market interests.

Finally, Sphericon will introduce DAISY to government authorities, where concern road safety is a major concern. The company is convinced that once the system has proven beneficial, it (as well as equivalent systems if available) is bound to become mandatory equipment on all road vehicles.

6. CONCLUSIONS

For over thirty years now, researchers have been looking for a solution that will allow the detection of a drowsy driver. None of the many ideas tried have resulted in a reliable and marketable product. Many approaches have been taken, some of which based on the steering dynamics but none of them had the element of a positive test – some dynamic criterion against which the performance of the driver can be compared and continuously assessed. Sphericon's breakthrough came about with the realization that (1) such a criterion, a built-in test, exists in the driving process where the driver continuously reacts to the disturbances caused by external forces, and (2) that the action of the driver and the action of the disturbances can be determined, separately, providing the test for the driver level of performance.

This project was the last, and most complex, in three phases. The first two phases dealt with the confirmation of certain aspects of the concept. This last phase, integrated all the elements that together make the concept work for the final validation of the concept.

The next stages that will lead to the implementation of the product include:

- Intensive testing for statistical evaluation of DAISY's performance which will include eye tracking (PERCLOS) as a criterion for the system's quantitative verification.
- Prototype development – in-vehicle, real-time prototype will be built and demonstrated
- Engineering and commercialization – re-design for production and extensive testing and evaluation, tailored for particular vehicle models. This is expected to take place in cooperation with vehicle manufacturer and a major automotive supplier. A transport company that will install test models for evaluation (beta site) will be sought. Appropriate standards will need to be identified or defined.

Additional issues will need to be addressed such as how to alarm the driver and legal questions.

A specific outcome of the work done in this project was the likelihood that the system can be fitted for after-market distribution (unlike what was thought earlier); this is in particular true for heavy trucks and motor coach applications. This would allow fast expansion of the product, possibly independently of the vehicle manufacturer, in these types vehicle where the need is more substantial.

Expansion of the capabilities of DAISY to detect inattentiveness of drivers due to alcohol, drugs or distraction will require further development work. Nevertheless, with the completion of the present project, the critical technological hurtle was removed: the ability to exploit the concept underlying the principles of DAISY have been confirmed.

The impact of the implementation of DAISY, once a widely used product, on transportation practice needs not much elaboration. It has the potential of removing major contributors to crashes and thus of reducing significantly the number of injuries and fatalities caused by crashes as well as their adverse effect on economy in the United States and worldwide.

7. INVESTIGATOR PROFILE

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Dan Omry is the founder and the CEO of Sphericon. Until the establishment of Sphericon, he was the Managing Director of Guidex Limited, a consulting R&D Company of which he was a co-founder in 1989. Guidex has initiated various advanced, multi-disciplinary projects and executed them jointly with the Israeli Ministry of Defense as well as with several hi-tech companies. Guidex has also consulted for major Israeli hi-tech companies on numerous projects in the areas of systems engineering, dynamics and aerodynamics, command and control, and simulations. In addition, Dr. Omry teaches courses at the School of Science in the Hebrew University in Jerusalem. Prior to Guidex, Dan performed research work at Stanford Research Institute (SRI) in Menlo Park, CA, and at NASA Ames Research Center, in Mountain View, CA. He held senior engineering (R&D) positions at the Chemical Systems Division of United Technologies and at the Marine Division of Westinghouse Electric Co., both in Sunnyvale, California, and in the Systems Division of Tadiran, in Israel. He received his Ph.D. Degree in Aeronautics and Astronautics from Stanford University, his M.S. Degree from Georgia Tech, and his B.Sc. Degree from the Technion - Israel Institute of Technology.

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