AC 2009-520: THE THEORY AND PRACTICE OF RACE-VEHICLE DATA ACQUISITION AND ANALYSIS IN MOTOR-SPORTS ENGINEERING EDUCATION

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Abstract

Motorsports Engineering has currently reached an unprecedented level of technical sophistication. This unique field of engineering specialization is at the vanguard of automotive research and development for terrestrial transportation. It deals with high performance ground-vehicles, engines, and conventional and alternative fuels that are subjected to extreme conditions in race competitions. At the heart of ground-vehicle racing is data acquisition and analysis. Virtually every racecar in motorsports competitions is equipped with computerized systems that help engineers, technicians and drivers to measure vehicle-physical parameters, understand and evaluate car driver behavior and interaction, and implement strategies to optimize overall performance. This paper discusses the principles and practice of data acquisition and analysis under real-world conditions, a core aspect of education and training of motorsports engineering and technology students at Old Dominion University of Virginia. Race-vehicle parameters, such as: engine rotational speed (RPM), lateral and longitudinal acceleration, vehicle speed, track position, and steering angle, are examined in the context of racecar testing at the track of the Virginia International Raceway (VIR) of Danville, Virginia. General configurations of modern data acquisition systems for race competitions, and integration of camera systems, GPS, and track mapping are also discussed. Examples of procedures for collection of data at the race and data analysis are presented, in order to illustrate the emphasis and educational character of ODU's motorsports engineering curricula, i.e.: Integration of theory and practice at real-life race track facilities, and racecar competitions.

INTRODUCTION

Motorsports Engineering is an innovative field of education that focuses on high performance ground-vehicles, and motorcar racing. Car racing is commonly viewed by the public as entertainment. In reality, motorsports is an intensely complex field that requires a significant level of engineering and high-end technology in order to achieve a clear objective: defeat the competition and win the race. [3,7,9,11]

Winning in motorsports brings considerable financial and technologic benefits to promoters, sponsors and automakers. As a result, motorsports has established itself as one of the most rapidly-growing industries in the US and worldwide. Furthermore, many experts agree that the golden age of national and international auto racing is occurring right now. Aware of this fact, car manufacturers nowadays make every effort to organize race teams and motorsports events, participate, compete and win.

It is clear for automakers and related suppliers that the validation of performance characteristics during race competitions is one of the most important means to build up the prestige of their national and international brands and models. This readily translates into new markets and profitability for vehicle manufacturers.

Since its humble beginnings - the first recorded car race took place in 1894, France. The race was a contest between vehicles invented by readily recognizable names in the automotive field, Karl Benz and Gottlieb Daimler - motorsports has been a field of uninterrupted invention and development.

Motorsports promotes ingenuity and continuously tests the bounds of human endurance and safety. Motorsports is an industry that has reached an unprecedented level of complexity and technical sophistication. It endlessly demands higher levels of vehicle performance and the understanding of the maximum number of functional parameters, and characteristics of driver-vehicle interaction.

Motorsports is, in most instances, at the vanguard of vehicle design, manufacturing and testing. In fact, motorsports is not only entertainment but a real opportunity for engineers, technologists and researchers to subject engines, body and structure of ground vehicles to extreme conditions that test and verify their durability, power, safety and aerodynamics.

Motorsports is indeed a dynamic industry. It attracts countless businesses and sponsors and offers a multitude of career opportunities for engineers, scientists and technologists.

MOTORSPORTS ENGINEERING AT OLD DOMINION UNIVERSITY

Motorsports engineering is a relatively new field of specialization in higher education. This is an educational program that focuses on the science and the technology behind race vehicles and race competitions.

In the early days of motor racing a very limited number of engineers were part of the teams since decisions in motor racing were mostly based on driver intuition, and empiricism of technicians and enthusiasts.[7]

This is no longer the case. Race competition nowadays is a highly sophisticated and technically-advanced enterprise. Engineers with adequate knowledge and training in the field have become indispensable members of race-teams. Automakers and race teams are quite willing to invest heavily not only on the latest hardware, but also on R&D and the technical support of engineers and technologists that can provide a winning edge during competitions.

The main branches of the engineering and the technology behind motorsports are: *Design, Manufacturing, and Vehicle Racing*. Engineers are needed in a large number of aspects within these branches and they work in teams towards achieving the common objective of all branches, i.e.: traveling with a ground-vehicle from a starting point to a finishing point as quickly as possible and win. [11]

To this effect, each technology branch of motorsports integrates a gamma of subfields that contribute to the success of the competing team, and where engineers play a crucial role, i.e.: to deliver a “winner” vehicle.

Consider for example the motorsports branch of *Design*. Since position and velocity are the key parameters of motion, engineers that design race vehicles are responsible for providing the driver with suitable means to control vehicle position, and change its velocity at the fastest possible rate, i.e.: maximum acceleration. Maximum acceleration in turn, requires a power system that provides the necessary force or forces to move the vehicle efficiently and safely. Therefore, forces, inertia, power, structures, aerodynamics, fuels, human factors, safety, etc. are all subfields integrated in the engineering design of the race vehicle. [6,8,10]

Intuition only is no longer the answer to modern needs in the design of motorsports vehicles or regular vehicles for that matter. Both, the ability to understand the underlying science, and apply analytical methods to optimize the design are now the norm of the day in the branch of Design, within the motorsports industry.

Motorsports engineering is multidisciplinary yet well-focused towards a common and clearly-established objective, i.e.: win in motor-race competitions. Educational programs that combine the fundamental engineering elements of the motorsports field, and graduates with good grasp of these elements greatly benefit the needs of this dynamic industry.

Old Dominion University of Virginia currently offers such educational programs. ODU currently offers a BSET with concentration in Motorsports and a MS Degree in Motorsports Engineering. Both, the bachelor’s and the master’s degrees focus on practice in close conjunction with theory. They combine engineering and technology elements that are specifically needed in the field of motorsports such as, mechanics, thermodynamics, power, aerodynamics, instrumentation and data acquisition, management and economics, in addition to a traditional mathematical and scientific foundation.[7]

Solid foundation and analytical skills in all these areas are needed if high performance vehicles are to be studied, understood, developed and tested in race competitions.

Central to performance analysis and the understanding of race vehicles on the track is the acquisition, storage and analysis of data. Virtually every racecar in motorsports competitions nowadays is equipped with computerized systems that help engineers, technicians and drivers to measure vehicle-physical parameters, understand and evaluate car driver behavior and interaction, and implement strategies to optimize overall performance.

The curriculum of ODU's Motorsports bachelor's program includes two courses that focus on Instrumentation and Data Acquisition for race-vehicles. The first course is offered at the junior level and is designed to provide basic foundation of instrumentation and experimentation. A suitable foundation in physics, particularly in electricity, optics, thermodynamics, and elementary electronics, are the required background for students taking this course. The sequence involves a senior-level course that is well focused on the use of Data Acquisition in real-life racing, and data analysis.[7]

Suitable and modern infrastructure for student instruction in this area has been installed and implemented at ODU's Engine and Drivetrain Laboratory located at the Virginia International Raceway located near the City of Danville, VA. Such laboratory is operational and is currently being used for student instruction and training. Additional information about this facility is presented below.

Examples to illustrate the character of this educational aspect within ODU's motorsports engineering curricula are presented and discussed in this paper. They are examples that have been performed with student participation, and have been developed for field-testing on a professional race track with the specific objective of providing real-life training to students enrolled in the motorsports program.

DATA ACQUISITION, AN INDISPENSABLE TOOL IN AUTO-RACING

Data acquisition, in general, is a relatively modern term that refers to computerized systems and procedures used to collect, store and analyze data. Such systems normally integrate hardware and software into specialized packages for use in engineering and science, or any application whereby physical data is needed to infer conclusions and provide a technical course of action.[1,9]

In the field of motorsports, there are several categories of data that can provide useful information to engineers and drivers in order to improve the "chances" to win a race. In all instances, gathering and processing information have become invaluable tools for engineers to examine and evaluate vehicle performance at the track.

There is a great variety of data acquisition systems commercially available that suits even the most modest budget. Figure 1, for example, shows a typical configuration of a data acquisition system offered by AIM Sports specifically designed for motor racing.

Both, the data collected and the analysis performed by the use of data acquisition systems can be subdivided into suitable categories. This subdivision normally depends on the intended application of a data acquisition system. In car racing, for example, it is common to break down the collected data into the following categories:

(a) Vital functions of the car,
(b) Driver Activity, and
(c) Chassis Physical Parameters.

The number of measurements that can be obtained in each category is only limited by cost. For example, measurements in the category of *Vital Functions* may include: oil pressure and temperature, water temperature, fuel pressure, gearbox and differential temperature, RPM, battery voltage, etc.

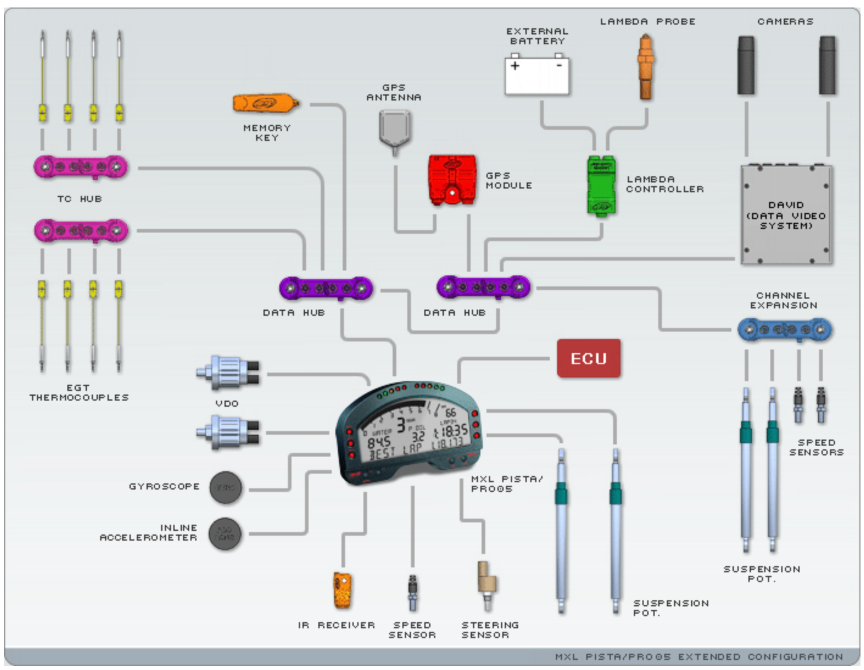

Figure1. Modular data acquisition system for car racing from AIM Sports a world leader DAQ company for motorsports.

Measurements in the category of *Drivers Activity* may include: throttle position, steering angle, and brake pedal position. *Chassis Parameters* measurements may include: vehicle speed, lateral and longitudinal acceleration (G-forces), steering angle, damper position, brake line pressure, tire temperatures and pressures, ride height, and suspension loads

Most of these parameters are normally measured and stored as a function of time and used by engineers either "real-time" or after the race in order to infer conclusions and provide recommendations to drivers and other members of the team. Graphical representations of these data help to visualize parameter *trends*, vehicle and driver *behavior* and greatly facilitate the analysis of data.

Two typical plots that are frequently used by engineers in car performance analysis are presented in figures 2 and 3.

The plot in figure 2 presents a trace of the vehicle speed along the track. This type of chart is commonly used by engineers to understand better the vehicle dynamics. Among other inferences the chart helps to make conclusions about the effects of changes made on the vehicle, or the driving style and peculiar reactions of the drivers at different zones of the track. Accelerations, braking periods, cornering speeds, top speeds, etc. can easily be observed and comparisons made among different laps in order to improve performance. Notice that track navigation may be part of the data acquisition system. This is extremely useful for the simultaneous coupling of measured parameters with the layout of the track (figure outset).

A plot of longitudinal acceleration such as the one presented in figure 3 helps to understand forward acceleration and/or break efforts, up-shifts to higher gear, effects of aerodynamic drag, etc.   In a similar way, plots of other parameters that the acquisition system is capable to measure allow the engineer to obtain overall or detailed views of occurrences that provide clues to improve and optimize vehicle and driver performance during competitions.

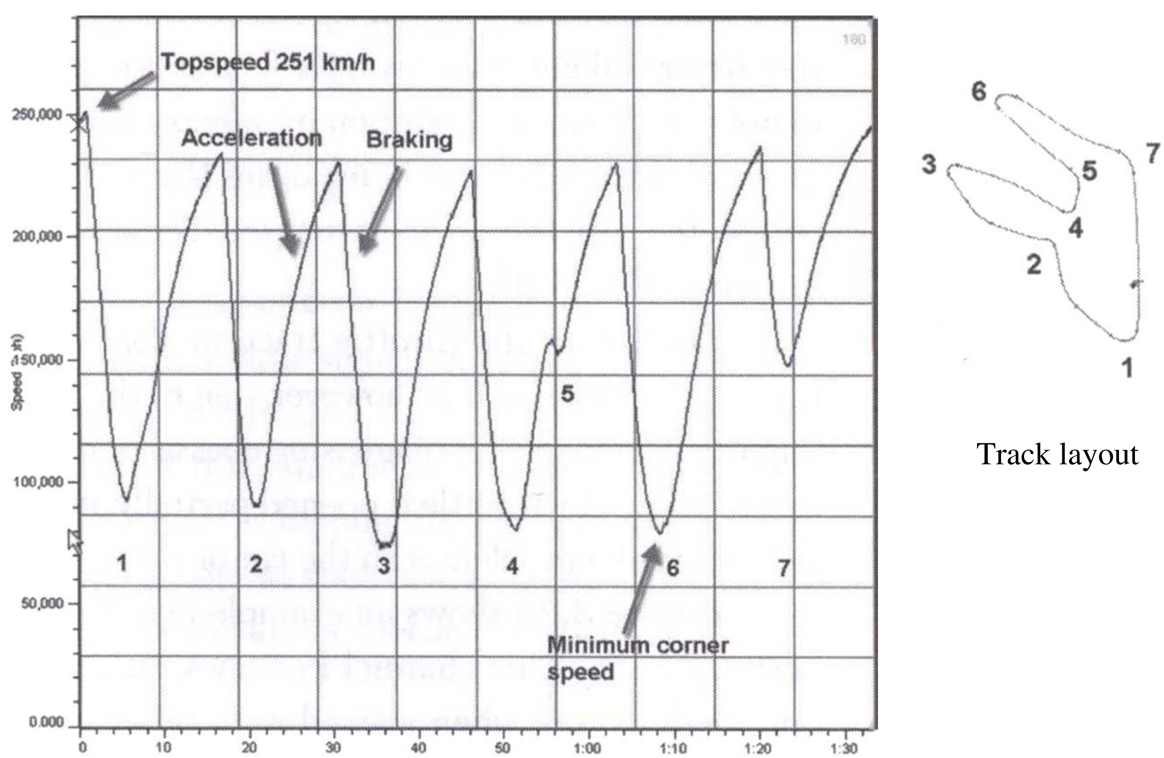

Figure 2. Example of vehicle speed versus time and track layout

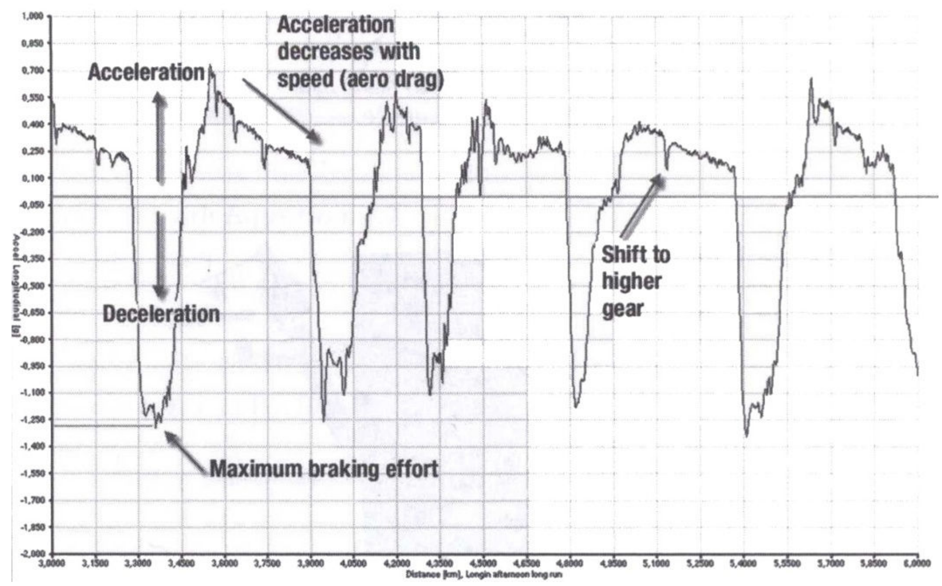

Figure 3. Example of longitudinal acceleration versus distance

The importance of data acquisition for car racing is evident. Engineering diagnosis and evaluation of vehicle-driver performance would be almost impossible without the use of data acquisition systems. Thus, a motorsports engineer must be well-versed in this field if he/she is to provide a competitive edge to the team.

Therefore, the coverage of underlying principles together with practice on data collection and analysis are essential ingredients of ODU's motorsports engineering education.

ODU's REAL-LIFE MOTORSPORTS TESTING AT THE "*VIR*"

VIRginia International Raceway (VIR), located in southern Virginia between Danville and South Boston, is one of the world's finest road courses. A road course is a race track that is designed to emulate an actual winding road (as opposed to an oval or drag configuration) but provides additional safety features such as additional run-off room and facilities to host major spectator events.

VIR hosts pro and club car and motorcycle races, a wide range of racing and riding schools, track days for cars and bikes, club events, off road driving, drifting and private test rentals during the course of any given year. VIR facilities are extensive including high end dining and lodging including a hotel, condos and a spa. Race facilities include the track which can be run in up to four separate configurations with two running at the same time using duplicate support facilities.

The primary (full course) configuration is a 3.27-mile long road course with 17 corners. The track follows the rolling countryside of southern Virginia and has a significant 130 foot vertical elevation change from the highest to the lowest point on the track. The longest straight is 4000 feet- almost a mile- which allows speeds up to 180 mph for some types of cars. Figure 4 shows the layout and aerial view of the VIR.

Figure 4. VIR track-layout and aerial view

The Virginia Institute for Performance Engineering and Research (VIPER)

One of the goals of the VIR track is to serve as a magnet for race technology activity in order to provide local economic growth. This is done in partnership with the IALR (the Virginia Institute for Advanced Learning and Research) and two leading institutions: Old Dominion University (ODU) and Virginia Institute of Technology, through the project known as the Virginia Institute for Performance Engineering and Research (VIPER).

VIPER is a national center for ground vehicle performance testing, engineering & research services specializing in racing, advance technology and performance vehicles. VIPER is divided into four different areas: (1) Aerodynamics, (2) Chassis / Suspension/Tire, (3) Driver, and (4) Engine and Drivetrain.

Old Dominion University operates the Engine and Drivetrain Laboratory located inside the VIR track and has three major areas of focus. The facility is designed to support hands-on instruction of undergraduate and graduate students enrolled in ODU's motorsports programs, conduct engine and drivetrain research, and operate as a self-supporting commercial entity.

Instructional Data Acquisition Test Outline

The goals of data acquisition tests at ODU's Engine and Drivetrain Laboratory are to teach basic data acquisition skills applicable to modern race cars and basic engine tuning theory and application. The lab supports four courses of ODU's motorsports curriculum. Major emphasis is placed on making the lab practice as realistic as possible by performing it in an actual race weekend setting at the track, and using a test car that would later qualify and race. Students are to become familiar with modern data acquisition software and data gathering, organization, analysis and interpretation techniques. Engine tuning theory is demonstrated in the lab by actual tuning of a race engine under normal race weekend conditions.

Test Car

The test car is an open wheel Formula style car designed specifically for road course use (See figure 5). It is a Formula Mazda which is a 'spec' car meaning that no major changes by teams to the cars are allowed (NASCAR is another example of a spec series as well). This is a cost and competitive advantage leveling rule that is used by many sanctioning bodies to control the total costs of the series.

The key to the Formula Mazda's affordability, popularity and reliability is the low maintenance power plant. The Mazda 13B rotary engine used in the car is not only capable to deliver 180 hp, but it does it with consistent reliability.

Figure 5. Formula Mazda, ODU's motorsports test vehicle at the *VIR*

It is not unusual for the sealed and rev-limited motors to remain in cars for over three seasons without a rebuild. Engines are sealed with tamper-proof devices to ensure that no modifications have been done internally. External adjustments, however, are legal and include carburetor jet tuning, fuel type, spark plugs and engine timing. Although each of these areas constitutes a relatively minor change, there are significant horse-power gains to be made by optimizing.

Race Car Specifications

• Dry Weight	1140 lbs
• Minimum Wt. with Driver	1350 lbs.
• Engine	Mazda 13B rotary
• Wheelbase	95 in.
• Power	180 hp
• RPM Limit	6850 rpm
• Quarter mile	11.3 seconds at 131 mph

Although the motor is sealed, drivers can make adjustments in other areas of the vehicle. Changes can be made, for example, to the ride heights, toes, cambers, casters, wing angles, gear ratios, and tire pressures. The race competition is to determine the best vehicle and car driver not based on expensive engines, but on clever adjustments and fine tuning of the vehicle and the skill of the driver at the track.

Data Acquisition System

The data system installed in the car used for this teaching exercise is an AIM MXL Pro integrated dash and data logger (See figure 6). The system monitors and displays important engine and car parameters and displays information on a display module with integrated logger and display module. The system records a total of 25 channels of data for later downloading and analysis representing all three areas of interest: car vital functions, driver activity, and chassis physical parameters.

For the purposes of this lab, a six-channel subset is chosen for detailed analysis in order to determine and optimize relevant engine operating parameters. The goal is to maximize engine power while preserving reliability. These parameters are: GPS location, vehicle speed, engine rpm, engine air/fuel ratio, and front and rear engine exhaust gas temperature.

Figure 6. AIM MXL integrated dash DAQ

Data is downloaded post-session and reviewed on a laptop computer. User-friendly AIM Interpreter software is used for analysis. The system can display the data in a myriad of fashions including time based graph, distance based graph, histogram, frequency analysis, measures applied to colored map, X-Y graph and lap animation replay. For the sample lab experiment discussed in this paper, the appropriate methods to display the data of interest are: distance based graph of single laps, histograms, and map-based measures.

GPS

A GPS receiver is fitted to the car and is capable of recording vehicle location within three feet (1m) at a frequency of five times a second. This channel is used to generate a track map (See Figure 7) which allows interpretation of important information including location on the track (straight or curve), and derivative channels such as speed.

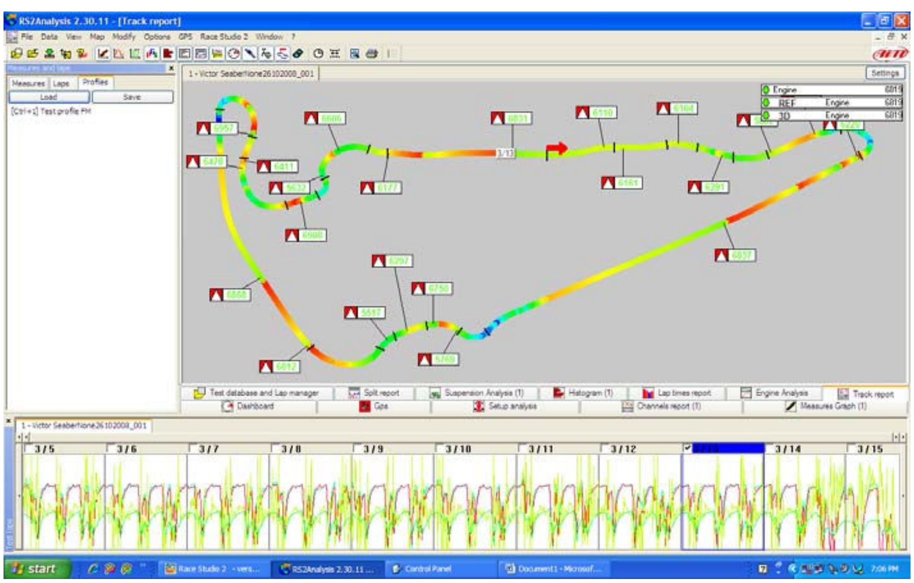

Figure 7. GPS-generated track layout

Vehicle Speed

Vehicle speed is determined using either the GPS receiver or one of the four wheel speed sensors fitted to the car. Generally, GPS speed is preferred over the wheel speed sensors for overall vehicle speed and position since wheel speed sensors are used primarily to look at wheel spin or *lock up*. However, wheel speed sensors provide insight of driver activity such as braking, and throttle applications techniques.

Engine RPM

Engine RPM is sampled from the engine's ignition system and is used to verify the throttle setting and look at events such as gear shifts which affect both EGTs and air-fuel ratio.

Engine air/fuel ratio

Engine air/fuel ratio (AF) is sampled by a *Bosch* wideband oxygen sensor and is the primary engine tuning tool. The sensor is capable to indicate directly whether the engine is running too *rich* or too *lean*, both crucial parameters of engine-power determination. Race engine tuning can be simplified for the teaching environment to primarily focus on operating the engine under race conditions in a fairly narrow AF ratio band of 12.0 to 13.0 with "safe" EGTs.

Exhaust Gas Temperatures

The exhaust-gas temperature (EGT) channels use thermocouples to measure the temperature of exiting exhaust gasses. This information is used: (a) to confirm the AF ratio sampled by oxygen sensor, and (b) as a safety parameter. Under full throttle conditions the exhaust gas temperatures should be within about 150 °F of each other and should not exceed 1725 °F for an extended period of time (over 2 seconds). Temperatures within this range are high enough to cause the entire exhaust system to glow "*red hot*" under operating conditions.

Figure 8 illustrates the transient behavior of front and rear EGTs in °F, (red and blue lines) as the vehicle accelerates. These temperatures become relatively stable at a distance of approximately 8550 ft, and they are below the critical limit of 1725 °F.

The figure also includes the trace of engine rotational speed (RPM, dark green line), and the AF ratio (yellow line). Notice the great variability of the AF ratio under transient conditions. This is where engine RPMs are used to determine gear shift as these shifts cause transient lean conditions.

Figure 8. Test trace of front and rear EGTs, engine rotational speed and Air-to-Fuel ratio

SAMPLE LAB ACTIVITY

Motorsports lab activities at the track are performed following the format of a typical racing-test day. It is common to run four test sessions throughout the day. First, the vehicle is thoroughly inspected at the lab facility, including the instrumentation and data acquisition system. Subsequently, the vehicle is readied for laps practice as announced by the track coordinators. Data collection starts at the moment of departure into the course. The data collected during the test run will be analyzed and studied in order to make changes in engine parameters that would improve engine performance during the following practice session. The data analysis and recommended changes are performed after each session.

In this sample test, the objective is to monitor the front and rear EGTs and the AF ratio, particularly at wide open throttle conditions within a course stretch that allows the vehicle and driver to achieve this condition (See figure 7, section of track indicated with 3/13). The data collected will be used to make carburetion changes in the engine in order to achieve optimum performance. Figure 9 shows parameter behavior of the vehicle at the stretch 3/13 of the track. Notice in particular, the relatively constant value of AF (approximately 12.8) within the stretch of maximum vehicle velocity.

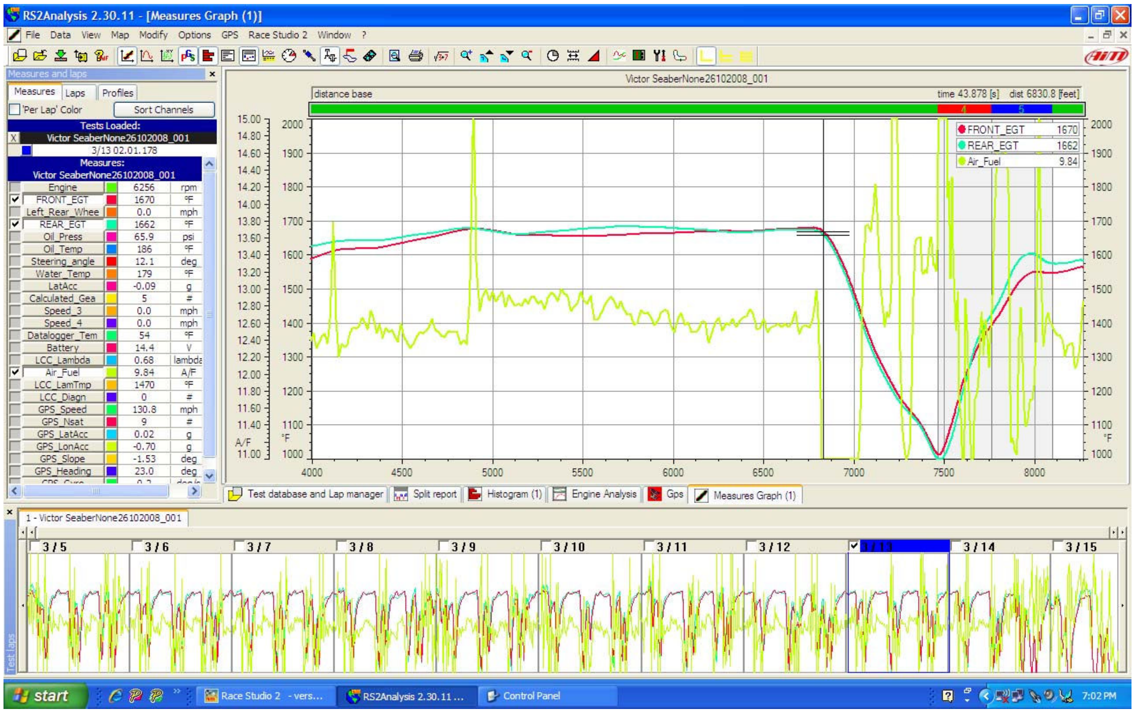

Figure 9. Trace of EGTs and AF in stretch of maximum speed

Figure 10 presents a sample histogram of EGTs. The engineer can easily conclude from it that such temperatures were always below the critical limit.

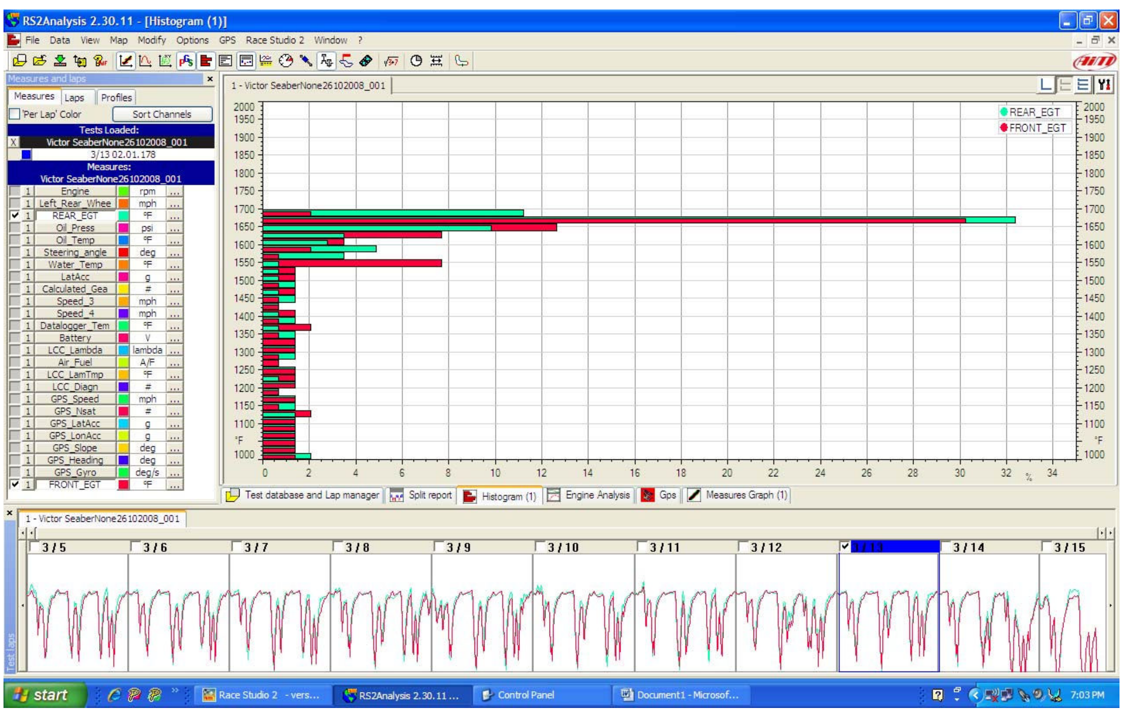

Figure 10. Histogram of EGTs

Tuning Tools

The tuning tools used during the test are carburetor parts designed to change the engine air fuel ratio. These parts are: carburetor main jets, air corrector jets, idle jets, idle jet trim settings, and accelerator pump jets. In the particular test case presented here, there were many combinations of tuning parameters during the four sessions, in particular because of unpredictable changes of ambient conditions changing (barometric pressure and temperature). Therefore a traditional DOE format was not possible. However, this constituted the major lesson learned in the real-world setting, i.e.: it is not always possible to gather data on all possible configurations, and therefore, past experience and a database of prior settings needed to be used to predict the results of changes.

Procedure

The test car was run on the track under real-world testing conditions and data was collected and analyzed. The six channels of interest were reviewed against target parameters and changes were made during all sessions to garner the optimum results. Changes were made to the main jets resulting in changes to both the air fuel ratio and the EGT's of the car. Emphasis was made to understand the effects of track conditions during the test: ambient temperature varied by 20 degrees F during the test which must be accounted for when making changes. Greater ambient temperatures throughout the day resulted in a richer mixture (lower EGT's and a lower air fuel ratio) with every 10 degree change equivalent roughly to a significant size change in main carburetor jetting.

Results

Lean AF mixtures combined with high EGTs on the track under the test conditions would result in catastrophic engine failure. This did not occur so the exercise was a success from that aspect. In addition, target values of AF mixture were achieved, thereby optimizing engine performance. As a primary educational goal, the test served well to expose students to the practical aspects of car racing. In this particular test, students observed and learned about the difficulties to make predictions with a limited number of measured parameters. This is because there is a large number of possible variations even though the test dealt with only a subset of race car performance variables.

Technical Report

Students involved in the experiment are requested to present a report of activity and analysis in a standard format. The format adheres to recommendations for technical writing and paper publication available through professional engineering societies. A manual of content and format guidelines for report writing is readily available for students enrolled in the motorsport program[5], and is provided by the course instructor.

CONCLUSION

Data acquisition plays an important role in race vehicle engineering design, testing and fine-tuning. There are innumerable combinations of signals, vehicle parameters, and driving characteristics that can be measured at race competitions or during practice sessions on the track. The knowledge gained from examining and analyzing these data allows the motorsports engineer to develop race strategies, improve driver performance, and determine performance potential of the vehicle as changes occur during the race.

Solid background on underlying principles and the applications of data acquisition and analysis is an essential aspect of motorsports engineering and motor racing. Cognizant of this important fact, Old Dominion University's motorsports engineering curricula includes highly practical training of students on the use of data acquisition systems for car racing in support of the theory imparted in lectures. Real-life tests and experiments performed on the track, such as the one presented in this paper, substantially enhances the instruction of motorsports engineering students.

This is possible because of ODU's association with the Virginia International Raceway (VIR), one of the finest road courses worldwide. VIR is located within the "Motorsports Alley" of Virginia and hosts a variety of race events, competitions and practices that help ODU students to be embedded in the motorsports environment. In addition, ODU's motorsports lab and test equipment operate within the premises of the VIR. This further facilitate the exposure of motorsports students to race teams, equipment, engines, vehicles, and data acquisition systems of current use in the industry.

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