Coaching Tools for High-Performance Driving

by

James Isaac Meyer

B.S., Mathematics

Rose-Hulman Institute of Technology

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master of Science

at the

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ABSTRACT

This project aimed to develop new tools to present and analyze data collected from racecars for the purpose of driver coaching. The tools developed are designed to quickly bring pertinent information to the surface and to further analyze the data for information that is not readily apparent.

The working environment for the project was the Barber Dodge Pro Series, an entry-level professional racing series. A data viewer program called DataWizard was developed as a test-bed for new coaching tools, based on interviews, observations and feedback at Barber Dodge events.

A method of track segmenting was developed as a new framework for organizing racecar data. Data from each lap is broken up by the section, turn, straight and brake zone, greatly improving the speed and ease of navigating though the data. A summary of vital statistics is created for each segment to bring key information to the surface.

Two methods of displaying information about the driving line were also developed. One uses color overlaid on a track path to depict the path radius, the other method uses icons to mark turn-in, track-out and apex points along a track path.

A racing GPS system was tested and suggestions are made as to how GPS data can be utilized along with data already commonly collected.

Thesis Supervisor: John Heywood

Title: Sun Jae Professor of Mechanical Engineering

Special Thanks

Betty Lou McClanahan – Executive Director of CC++, The Car Consortium at the MIT Media Lab. Provided funding and support for the project.

Barber Dodge Pro Series – Official Entry Level Professional Race Series of Championship Auto Racing Teams. Provided the working environment for the project.

Jeremy Dale – Series Director

Louis D'Agostino– Series Engineer

Gregg Borland – Series Data Acquisition Guru

Nick Longhi – Driving coach and CFO of grandprix.com. Provided racing background and introduction to the Barber Dodge Pro Series.

Josh Browne – Driving coach and racecar engineer. Provided racecar engineering and technical ideas throughout the project.

About the Author

James Meyer is native of Spearfish, South Dakota. He attended Rose-Hulman Institute of Technology in Terre Haute, IN and graduated with a B.S. in Mathematics in 1999. He was the Chief Mechanical Engineer of the Solar Phantom Project, Rose-Hulman's solar car team, where he designed Solar Phantom V, which competed in Sunracye '99.

After graduating, he worked as an engineer at RAMVAC Corporation in Spearfish, South Dakota, where he designed dental vacuum systems and served as computer system administrator.

At Massachusetts Institute of Technology he worked in the Sloan Automotive Lab, and served as President of the MIT Solar Electric Vehicle Team. He also attended the Skip Barber Driving School, a training school for racing drivers.

James enjoys swimming, running and bicycling. He competes in both road and mountain bike races as well as triathlons.

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1 Project Background

The goal of this research is to help racecar drivers, engineers and coaches to more quickly and effectively extract important information from car data to make the racecar go faster. Modern racecars employ sophisticated data acquisition systems that record many aspects of vehicle behavior. The amount of data recorded can be overwhelming, which can inhibit the effectiveness of the data. The purpose of this research is to reduce the "data smog" and increase the usefulness of the data through organizing, summarizing and analyzing.

A computer program called DataWizard was developed and written to implement these more sophisticated data viewing methods. DataWizard utilizes a new framework based on track segmenting to better organize data, instantly provides summaries of segment data and attempts to better display the driving line.

1.1 Research Background

The Barber Dodge Pro Series served as the working environment for the project. The Pro Series is the entry-level racing series in the Championship Auto Racing Team (CART) ladder. Entry-level professional drivers compete in identically prepared Raynard-Dodge open wheel racecars at CART events in the United States and Canada. In an effort to help the drivers learn and grow, the series also employs driving coaches to help drivers and all data is collected centrally and is accessible to all drivers. This learning environment and open data policy gave the ideal environment for study. The author attended Pro Series races during the summer of 2001 and helped with data collection, listened in on driver coaching sessions and received a copy of all data collected during practice, qualifying and racing.

This project is funded through the CC++, The Car Consortium at the MIT Media Laboratory. CC++ receives funding from major automobile manufactures and suppliers including DaimlerChrysler, Ford, General Motors, Lear Corporation and Motorola.

Professor John Heywood the director of the MIT Sloan Automotive Laboratory supervised the project.

1.2 Racing Background

Driving a racecar is an optimization process. The idea is simple; drive the car through the course in the least amount of time possible. This requires optimization of both the techniques and strategies the driver employs, as well as optimization of the car design and set-up. Data is crucial to achieve this, be it quantitative or qualitative. At minimum, a stopwatch, a tachometer or another car is needed to reference performance. At the other extreme is Formula 1, where during testing, over a hundred separate channels of data are recorded, providing megabytes of data per lap that is reviewed by teams of engineers.

1.2.1 Driving Fast

Even with all the complexity found in the driver-car system, the basic strategy employed by racecar drivers in fairly simple and is common to nearly every form of auto racing. The basic strategy for driving fast comes in three steps: Driving Line, Exit Speed and Entry Speed.

Driving Line

The first step to building lap time is the driving line. The driving line is the path along the road above which the center of gravity (CG) of the car passes. The ideal driving line is largely defined by the course boundaries and characteristics and to a lesser extent, the vehicle characteristics. The cornering ability of the car limits cornering speed, so the line taken through each corner will tend to maximize the corner radius. Changes in track elevation, camber and surface also significantly affect driving line. Mathematically calculating the ideal driving line is very challenging, however in practice it is far simpler. Drivers can find the driving line by observing other drivers, reading the rubber embedded on the track surface from other cars, as well as the feel developed from driving on similar corners on other courses. All together, experienced drivers can find the ideal driving line on a new track instinctively.

Exit Speed

The next step to building lap time is exit speed. Exit speed is the car speed when the driver finishes the turn, with the steering wheel back to a centered position. Mathematically, exit speed is the speed of the vehicle when the path curvature falls below a specified threshold. Exit speed is important because it dictates the speed along the ensuing straightaway. Higher corner exit speeds mean higher straightaway entry speeds and lower straightaway times. Exit speed is a function of how well the driver navigates the corner. It is common practice for drivers to glance at the tachometer at the end of every corner to measure improvement. Corner exits and straightaways constitute the majority of the length of a racetrack; therefore lap time is a strong function of the average speed over these sections.

It is important to note that exit speed is not necessarily a function of entry speed. Very low entry speeds will limit the exit speed due to the inline acceleration performance capabilities of the car. Too high of an entry speed will also limit exit speed due to difficultly making the car stay on the correct driving line. In the middle is a range of entry speeds that have very little effect on exit speed.

Entry Speed

The last piece to building lap time is the entry speed. Entry speed is the vehicle speed at turn-in. As the vehicle approaches the turn-in point, the drive uses visual cues to mark the point at which to decelerate the vehicle, either by releasing the throttle (lifting) or applying the brakes. The driver increases braking pressure and moves the braking point forward on successive laps until the exit speed is reduced. Changing road conditions (sunlight, rain, etc.) strongly influence the braking point as does changing vehicle characteristics, such as tire temperature and pressure and fuel load. For maximum performance, the braking point will vary from lap to lap based on the driver's judgment. Most overtaking occurs as a direct result of braking zone performance, further emphasizing the need for drivers to properly judge braking points and pressures. Because braking zones comprise a small percentage of the track length, the potential for decreasing lap time is limited. However to achieve maximum performance, maximizing entry speed is crucial.

These three steps represent the basis for driving racecars. All the advanced techniques and strategies employed by drivers relate back to these fundamental principles. The purpose of looking at car data is to optimize the execution of these three steps.

Going Faster, a book by Carl Lopez of the Skip Barber Racing School, gives a more in-depth explanation of racecar driving strategies and techniques.

1.2.2 Data Acquisition Hardware

The data acquisition systems vary greatly from series to series. NASCAR outright bans data acquisition systems while in others data acquisition systems are at the heart of the racing strategy. Although the size and complexity of data acquisition systems vary greatly, there are several components that are common to their design and construction.

A data acquisition system is composed of a centralized unit that contains the system memory and processor. The processing power and memory available varies greatly from one system to another. Smaller and older systems may have only 256kb of memory and do little processing, whereas newer larger systems have in the neighborhood of 128Mb of memory and can do complicated real-time processing of data. An LCD driver display is usually connected to the logging unit to serve as the driver's instruments. For some applications a radio modem, usually 900MHz or 2.4GHz spread-spectrum, is used to transmit selected data back to the pits in real-time. Data in the logger's internal memory is downloaded when the car comes to a stop in the pits through a high-speed serial or parallel link to a computer. This can take a number of seconds and is not done during racing pit stops.

Inputs to the logging unit come from an array of sensors from all over the car. Again the number and type of sensors can vary greatly from system to system. During testing and practice more sensors are used than in qualifying and racing. Below is a summary of common sensors used.

Driver Inputs	Steering Position, Throttle Position,
	Brake Pressure (F&R), Gear shift position
Vehicle	Wheelspeed (4), Lateral Acceleration, Inline Acceleration,
Performance	Pushrod (Spring and Damper) Loads (4), Shock Displacements (4),
	Chassis Ride Height (3)
Engine	RPM, Oil Temp, Oil Pressure, Fuel Pressure, Water Temp

1.2.3 Data Analysis Software

Each data acquisition system manufacturer usually writes a proprietary data viewer program for analyzing the data. These systems vary greatly in features and sophistication, but there are some common functions. Most systems can display the data from multiple laps on a distance graph, show the raw data from a point selected on the graph, create a track map for visual reference, and will export data to a text file for manipulation in an external program such as Excel or Matlab. More sophisticated systems can create X-Y plots of one variable verse any other, show histograms, create frequency domain plots and attach to vehicle simulation modeling programs.

1.3 Data Analysis

Once the data is collected, the next step is to utilize it to improve performance. The data must be inspected for important bits of information that indicate how the car setup should be modified or where driving style and strategy should be modified. In raw tabular form, the data is almost meaningless – a seemingly endless array of numbers. But in a graphical form, as shown most data viewing programs, the data is much easier to read. With the help of a track map, the user can determine what part of the graph relates to particular track positions and can begin to sort out where improvements can be made.

In practice, the recorded data alone is insufficient – it must be combined with the driver's comments for maximum effectiveness. Here the depth and accuracy of the driver's memory is very important. Even with hard data and a driver with great memory, it takes an experienced individual to focus in on the most important areas for improvement.

This whole process is complex and many times qualitative in nature. Some parts are routine and algorithmic while others rely on feel and experience. The software must be designed to give the user data in a form that is meaningful and should facilitate analysis without being overly cumbersome.

To create such a system, it is useful to refer to the knowledge pyramid. At the base is Data then Information and then Knowledge. Along side are listed the different activates needed to ascend the pyramid. Currently data analysis software does the first step, Collecting, and also performs some Organizing, leaving the other tasks to the user. Data analysis software should be able to do more, namely extensive organizing and summarizing and some analysis. This will transfer repetitive and algorithmic manipulation to the computer, leaving the user to concentrate on the remaining steps.

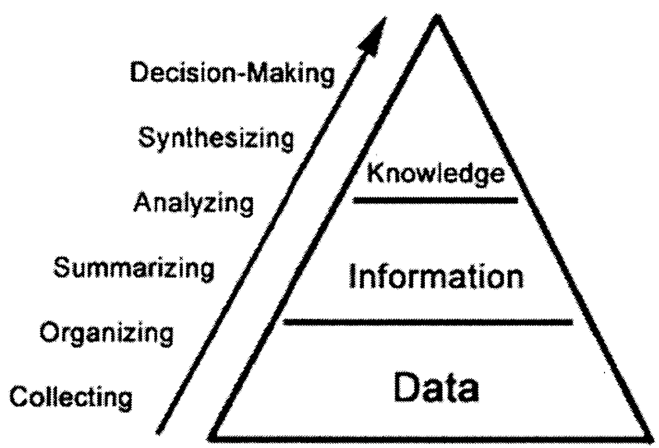


Figure 1.1

2 Organizing Data

Most data analysis programs store data sets by the "outing" and allow the user to view laps within the outing. The laps start and end points are identified with the use of an inferred beacon placed trackside and a detector on the car. The detector senses the beacon as the car drives by which allows the data acquisition system to separate the laps. The user navigates the data lap by lap and usually has the ability view two laps simultaneously and to zoom in on areas of interest. This still requires some thought and effort to carefully study particular sections of the track on multiple laps. Much more organization can be done.

One of the most common tasks the user does is to compare data on the same course segment between two laps. Therefore the organization system should automatically break up the course into track segments and allow for easy navigation.

2.1 Segmenting

DataWizard breaks up the track into segments that form a framework for organizing all data collected from the car. The user navigates through the data by selecting the desired segment from a list (for example Back Straight, Big Bend, Turn 7, etc.) When a particular segment is selected, the program zooms in and highlights the segment on the map, zooms in on the graph of the data and displays short summary of the critical information. This greatly improves the navigation speed and accuracy, allowing more investigation to be accomplished in a given amount of time.

2.1.1 Finding Segments

After data is recorded on the car during an outing and is downloaded to the computer, the user will select a lap to use as a "map lap". The map lap is usually the fastest lap in the outing. The data from the map lap is then used to find the segments and to make a picture of the track (a process covered in Section 3.1).

Finding the segments in the map lap is a purely algorithmic process based on the definitions of the segment types. The segments are based on the speed, lateral acceleration and instant radius data from the map lap chosen by the user.

The following example steps through this process for finding "Section" segments from the map lap. Sections are a type of segment that starts where the driver begins to slow down for a turn and ends just before slowing again.

Figure 2.1 is a graph of speed verses percent lap time completed for the map lap.

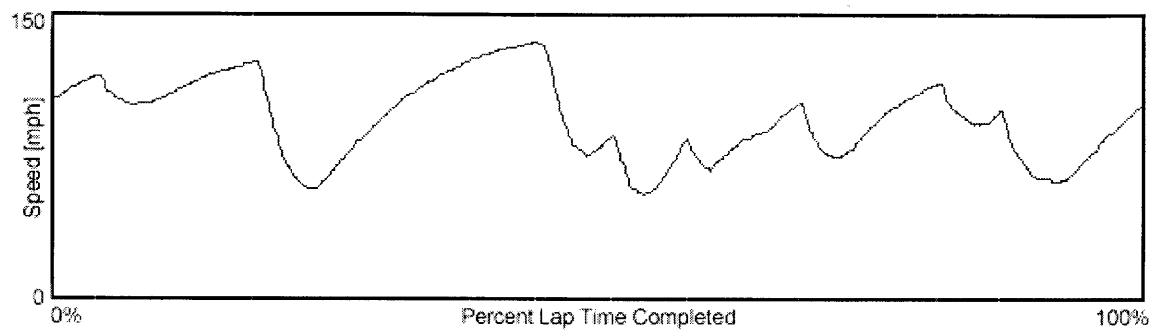


Figure 2.1

The definition of a Section segment says that the segment starts where the driver begins to slow down, right at the maximum speed point. DataWizard goes through the speed data from above and marks each local maximum speed point. Each Section segment is the space in between the local maximum speeds. Figure 2.2 shows the speed data with the segments overlaid on top.

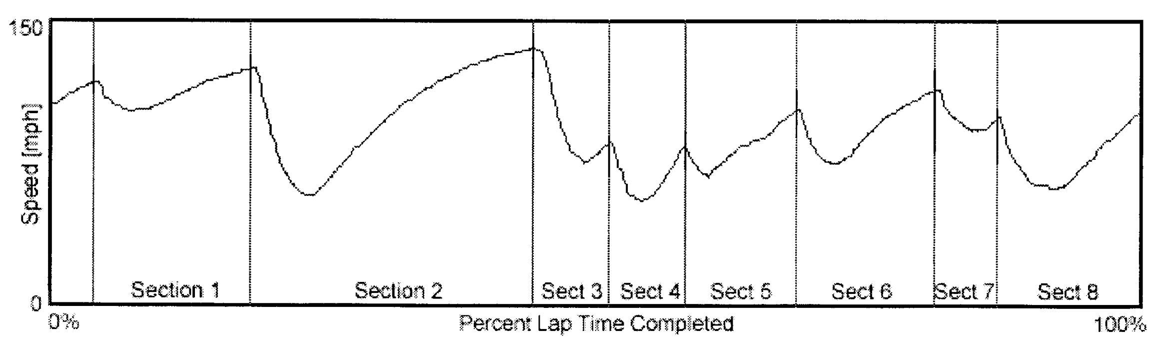


Figure 2.2

Now that the Section segments have been found, DataWizard saves the start and end points so that they can be applied to other laps during study. Figure 2.3 shows the Sections segments ready to be applied to other laps.

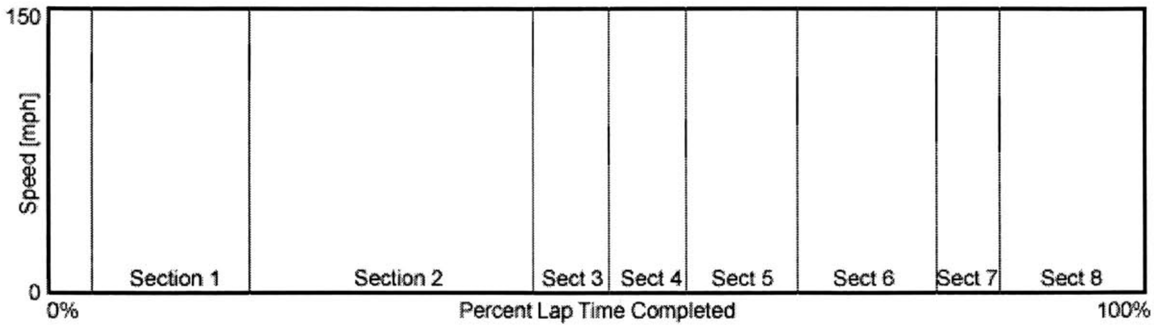


Figure 2.3

When other laps are studied, they are placed in the framework from above. Figure 2.4 shows other laps placed in the Sections found from above.

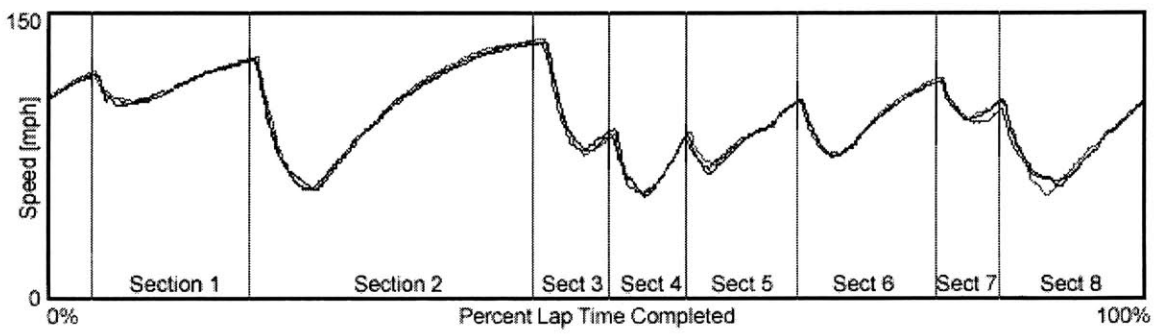


Figure 2.4

This process is repeated for each type of segment. Figures 2.5 shows two more types of segments Acceleration Zones and Deceleration Zones, as found from the same data.

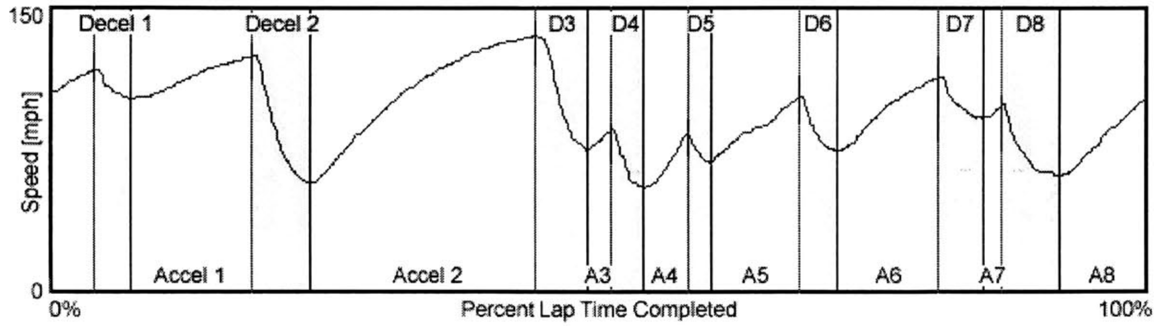


Figure 2.5

Figure 2.6 shows Straights and Turns found from the same map lap as above. Here the path curvature is used to separate identify the segments. Path curvature is a measure of how curved the path is at a particular location and is calculated from the speed and lateral acceleration ($c = a/v^2$).

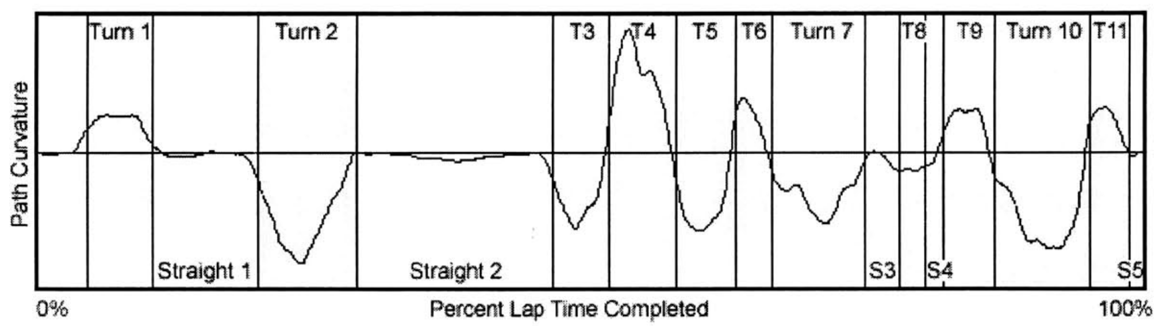


Figure 2.6

Figure 2.7 is a screen-shot of the DataWizard program. The map lap has been loaded and the segments have been found. Along the left side is the Lap Explorer that lists out the segments available. To the right of the Lap Explorer is the Select Laps menu that allows the user to select the file and laps to view. Five laps can be viewed simultaneously. On the right is the viewing window, which contains Segment Statistics (described in Section 2.2), the data at the cursor location, plot of the path curvature, speed, throttle position and engine RPM and finally a map of the course.

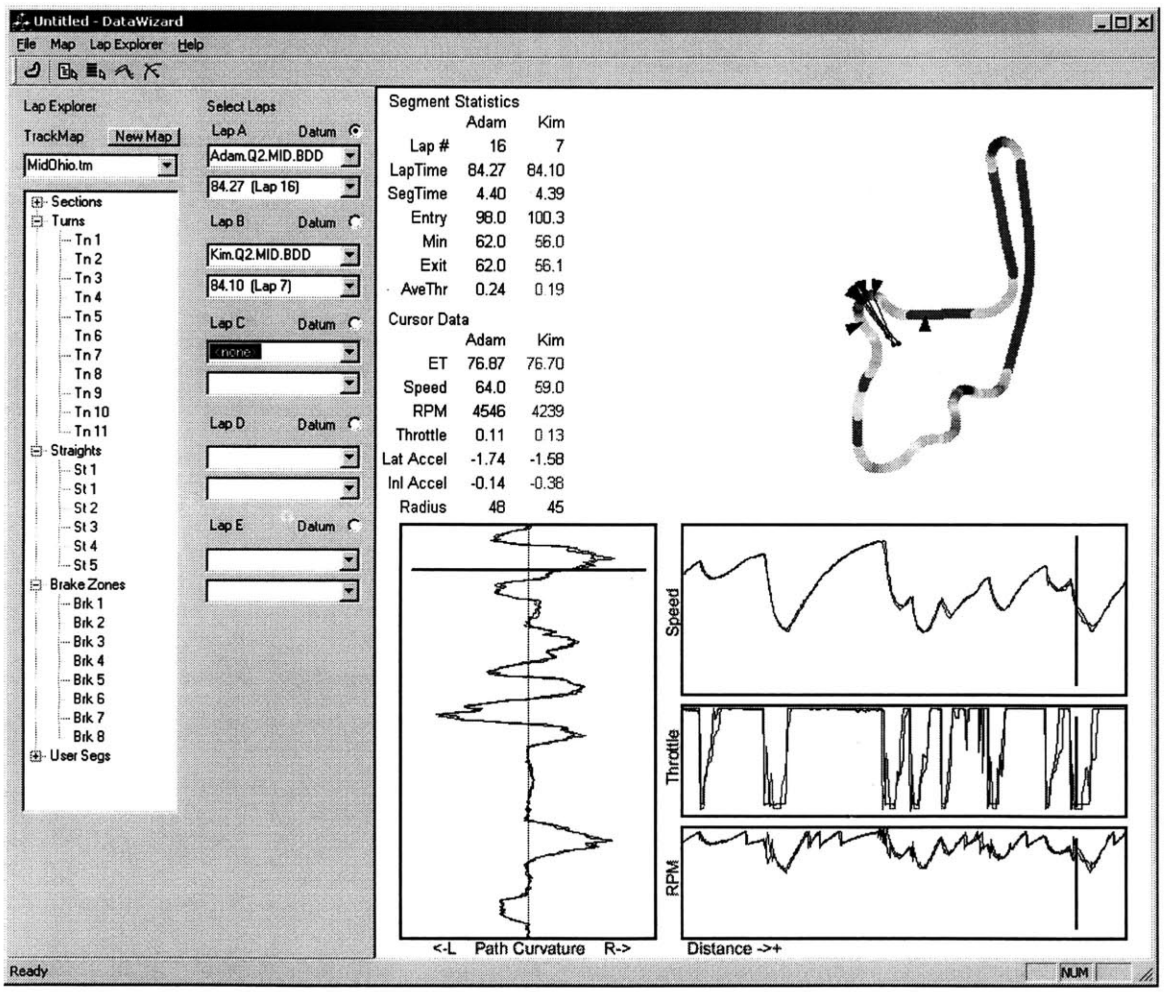


Figure 2.7

Figure 2.8 is a screen-shot of the DataWizard program after Turn 2 has been selected. DataWizard has zoomed into Turn 2 on the map and the plot windows. The segment statistics for Turn 2 are also shown.

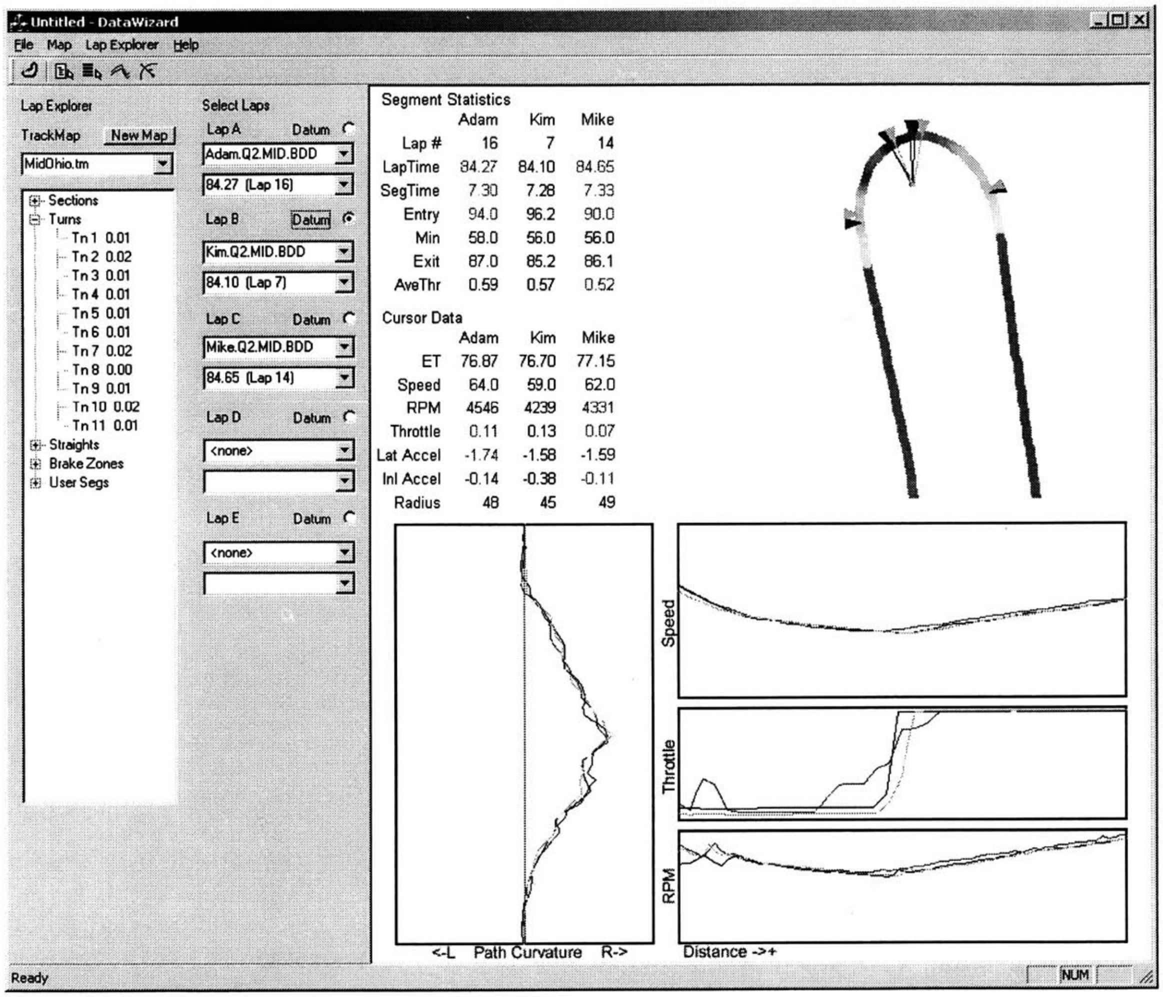


Figure 2.8

2.1.2 Segment Types

The most obvious segment types are straights and turns, but others such as brake zones, turn entries and exits are useful during analysis. Below is a description of a number of different segment types. The segments implemented in DataWizard are Sections, Straights, Turns and Brake Zones.

Section Driver –A section starts where the driver begins to slow down for a turn and ends just before slowing again. Sections are useful because the time required to complete a particular section is largely unaffected by the previous section. This allows section times for different laps to be compared independently.

Data – The continuous portion of track between local maximum speeds.

Straight Driver – Parts of the track where the car is going straight.

Data – A continuous portion of track where the instant radius is greater than a specified value. (Typically 500m)

Turn Driver – Parts of the track where the car is turning.

Data – A continuous portion of track where the turn radius is less than a specified value. (Typically 500m)

Brake Zone Driver – The last part of a straight where the brakes are applied.

Data – A continuous portion of track on a straight where the car speed is decreasing. (The overlap of a straight and a deceleration zone.)

Deceleration Zone Driver – Deceleration zones begin where the brakes are applied and follow down into the apex of the turn where the car is slowest.

Data – A continuous portion of track where the speed of the car is decreasing.

Acceleration Zone Driver – Acceleration zones begin at the apex of a corner where the car is slowest and extend out to where the brakes are applied.

Data – A continuous portion of track where the speed of the car is increasing.

Turn Entry Driver – The start of a turn down to the apex.

Data – A continuous portion of track on a turn where the instant turn radius is decreasing.

Turn Exit Driver – The apex of the turn out to the end of the turn.

Data – A continuous portion of track on a turn where the instant turn radius is increasing.

2.2 Statistics

Once the map lap has been loaded and the segments defined, other laps can be viewed using the resulting framework. When a lap is viewed, the user can select a segment of interest, like a particular turn. DataWizard then displays a summary of the vital statistics for that turn in the selected lap.

Figure 2.9 is a sample of the statistics output. These statistics compare the performance of three drivers, Kim, Mike and Adam through Turn 2 from above.

Segment Statistics

	Kim	Mike	Adam
Lap #	7	14	16
LapTime [sec]	84.10	84.65	84.27
SegTime [sec]	7.58	7.64	7.60
Entry [mph]	105.2	99.8	102.0
Min [mph]	56.0	56.0	58.0
Exit [mph]	85.2	86.1	87.0
AveThr	.55	.50	.59

Figure 2.9

The segmenting process has identified the start and end point of the turn and the statistics have been compiled. First shown is the lap number of the lap selected. Next gives the time for the full lap, in this case Kim was the fastest. Next is the time taken to pass through the segment, again Kim is the fastest. Also shown are the entry, minimum and exit speeds through the corner. Kim had the fastest entry, but Adam had the fastest minimum and exit speeds. Adam also had the greatest average throttle position, indicating that he was on the gas more.

Kim's lap was selected as the 'datum' or the reference to which the others are compared. The datum lap's statistics are always shown in black. The statistics for the other laps are shown in either blue (indicating better performance than the datum), red (worse performance than the datum) or in black (equal performance). This coloring scheme helps to the user to quickly identify areas of strength or weakness.

A set of statistics similar to above is found for every segment – all the turns, straights, brake zones, etc. Some statistics are applicable to all types of segments, such as segment time, while others are more specific. For example, in brake zones a measure of brake usage, such as integrated brake pressure or average inline deceleration is applicable, whereas in turn exits integrated throttle is more useful. The statistics shown for each segment can be modified according to usefulness and user preference.

There are a number of statistics that are of interest in different situations. Below is a description of some primary statistics of interest.

2.2.1 Statistic Types

<u>Local Metrics</u>

Elapsed Time	The elapsed lap time at the beginning of the segment. Gives an indication of how much time has been gained or lost up to the current segment.
Segment Time	The amount of time the car took to complete the segment. Useful in comparing the performance in a particular segment between two laps.
Integrated Throttle Position	The throttle position integrated over the segment. Gives a measure of how much engine power was used over the segment.
Integrated Brake Pressure	The brake pressure integrated over the segment. Gives an indication of how much brake was used.

Point Data

Entry Speed	The speed at the starting point of the segment. Entry speed is an indicator of braking performance prior to entry and how comfortable the driver feels about a particular corner.
Exit Speed	The speed at the end point of the segment. Exit speed is an indicator of driver performance within a turn and dictates the speed of the car along the following straight.
Minimum Speed	The minimum speed of the car in the segment. Minimum speed is an indicator of driver performance within a turn.

Event Finding

Braking Point	The location on the track where braking was initiated. Useful in comparing data between laps.
Full Throttle Point	Location on the track where the throttle reached wide-open. Useful in comparing data between laps.

3 Driving Line

Finding the correct driving line is the most basic step to driving fast. Most experienced drivers find the best driving line instinctively, but for developing drivers it is less obvious. Ideally the data collected on the car would include precise information about the driving line, but there are a number of challenges involved.

Currently most data viewer programs can make a track map for visual reference while viewing data. The track map is calculated from the speed and lateral acceleration of the vehicle. With some additional assumptions, this is accurate enough for a qualitative reference, but due to inherent errors is not precise enough to provide a good basis for careful driveline analysis.

The Global Positioning System (GPS) can give fairly accurate driving line information. The cost of GPS has been decreasing and it is just starting to be used in racing applications. It is yet unclear if its use will become widespread.

3.1 Inertial Mapping

Given speed and lateral acceleration data it is possible to map the path of the car. The wheelspeed sensor measures the forward movement of the car, while the accelerometer measures changes in the direction of the car. This is a form of inertial navigation, because the accelerometer measures changes in the inertia of the car. Given these measurements around the entire track, it is possible to add up all the little changes in position to calculate the path of the vehicle through space.

3.1.1 Map Creation

Most data viewer can create a picture of the track from data recorded on the car. The following discussion outlines the basic algorithm employed by these programs and DataWizard.

The data set contains the speed and lateral acceleration of the car at a fixed sample rate, usually around 10 to 25 samples per second (Hz). For each data point, the forward motion of the car can be calculated from the speed of the car. If the sample rate is 10 Hz, and the car is traveling 100 kph, then the car moved 2.78 m forward between samples. In general the forward motion of the car is calculated by

$$\Delta y_i = v_i \cdot \Delta t$$

Similarly the lateral motion of the car can be calculated from the lateral acceleration. If the car is turning at 1 g (9.8 m/s^2), then during the 0.1-second time between samples, the car moved .098 m to the side. This is expressed by

$$\Delta x_i = a_i \cdot \Delta t^2$$

Now that the forward and lateral motion of the vehicle has been established, the next step is to find the heading. The initial direction of the vehicle can be chosen arbitrarily, based on user preference. The change in heading during each sample time can be expressed by the ratio of lateral motion to forward motion. This will give the change in heading in radians. (To be precise the heading change is the arctangent of the ratio, but heading changes for each sample are small (<1deg), so the arctangent can be neglected.)

$$\Delta\theta_i \approx \frac{\Delta x_i}{\Delta y_i} = \frac{v_i}{a_i \cdot \Delta t}$$

The heading at any particular point on the track is found by adding up all the little heading changes from the start point to the point of interest.

$$\theta_n = \sum_i^n \Delta\theta_i = \sum_i^n \frac{v_i}{a_i \cdot \Delta t}$$

The X-Y position of the car can be found by using the forward and lateral movements of the car in conjunction with the change in heading. Mathematically this is best expressed in matrix form. This allows the position of the car to be mapped out for the whole lap.

$$\begin{bmatrix} X_n \\ Y_n \end{bmatrix} = \sum_i^n \begin{bmatrix} \sin(\theta_i) & \cos(\theta_i) \\ -\cos(\theta_i) & \sin(\theta_i) \end{bmatrix} \begin{bmatrix} \Delta x_i \\ \Delta y_i \end{bmatrix}$$

3.1.2 Mapping Errors

The errors in the process are readily apparent. Figure 3.1 shows a typical output of the mapping algorithm.

Figure 3.1

The most obvious error is that the endpoint of the lap does not match up with the start point. This and other errors arise from several sources.

Wheelspeed Sensor – Most wheelspeed sensors are proximity sensor that pulse several times per wheel revolution. Speed and distance traveled are calculated by pulse frequency and wheel size. The sensor itself requires no calibration, however an accurate wheel diameter must be used. The largest errors come from the tire slipping across the ground and brake lock-up. When one sensor is used it is placed on a non-driven wheel to eliminate wheel-spin error during acceleration, however braking still produces errors. Under hard braking the slip ratio of the tire can easily be 10% or much more if the tire locks up. Though errors in the measurement of forward motion produce errors in the map, they are not the primary cause of the distorted map shown in Figure 3.1.

Lateral Accelerometer – Lateral accelerometers work using the piezoelectric effect of stressing a small quartz crystal. The two main errors are a static offset (indicating an acceleration while motionless) and scaling (reading 0.9 g's in a 1.0 g turn). A fixed offset is very common error seen in racecar data. Because the lateral accelerometer measures the change in direction of the car, these errors will greatly affect the map.

Summations – The position of each point is a function of all the previously calculated points. Therefore any bad data points or other errors will accumulate as the points are summed. A heading error of one degree will mean a 17 m error one kilometer down the road. The algorithm is inherently sensitive to any errors in the data.

Heading Assumption – One error arises from an assumption made in the mapping algorithm – that the forward direction of the car is the same as the direction in which the car is traveling. Obviously there are many times when this is not true. Extracting maximum performance from a racecar requires that the driver maintain a controlled "drift" through a corner, usually of 3-8 degrees, but at times far more. Though errors are introduced for small slip angles, the effect is minimal. Larger slip angles (>10 deg) will cause noticeable distortion in the map.

3.1.3 Error Correction

Some of the errors that arise in mapping can be corrected with a few additional assumptions. For closed circuit tracks, the car heading at the start is the same as the heading at the end, and similarly the start and end points of the map must match. Corrections are made based on these two assumptions.

3.1.3.1 Accelerometer Offset

The most common error in the instrumentation is a fixed offset in the accelerometer; therefore a correction term (a_o) is added to the mapping equations.

$$\Delta x_i = (a_i + a_o) \cdot \Delta t^2$$

$$\theta_n = \sum_i^n \Delta\theta_i = \sum_i^n \frac{v_i}{(a_i + a_o) \cdot \Delta t}$$

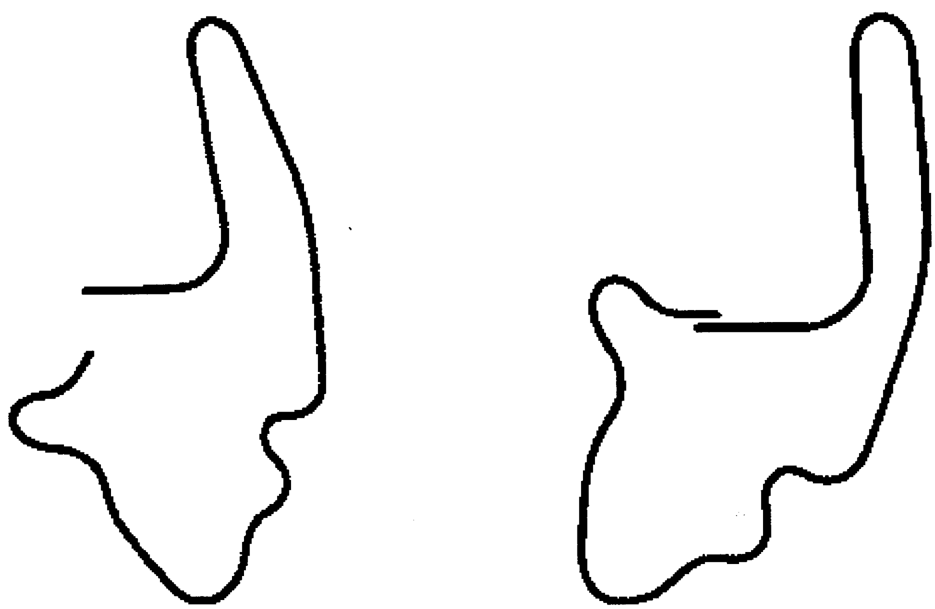
To find the best value for the correction term, the first assumption is used, that the start heading matches the end heading. Over the course the car will turn a 360° either to the right or left. Therefore the last heading must be ±360° or $\pm 2\pi$ radians. (For tracks that cross over themselves, such as Suzuka, the final heading must be a multiple of 360° or 2π radians.)

$$\theta_N = \sum_i^N \frac{v_i}{(a_i + a_o) \cdot \Delta t} = \pm 2\pi$$

The correction term can be found with some algebraic manipulation.

$$a_0 = \frac{1}{\sum_i^n \frac{1}{v_i}} \left[-\frac{\theta_N}{\Delta t} - \sum_i^n \frac{a_i}{v_i} \right]$$

This correction term is the fixed offset for the accelerometer. When added to all the accelerometer data, it will guarantee that the start and end headings will match. Figure 3.2 shows a map before and after the correction term is applied.



Before Accelerometer Correction After Accelerometer Correction

Figure 3.2

The accelerometer correction fixed the heading error as desired. Although the start and end heading now match, the positions do not line up. Unfortunately there is no obvious instrumentation error that can used to adjust the match of the points. However, a brute force method can be used to pull the end into alignment with the start.

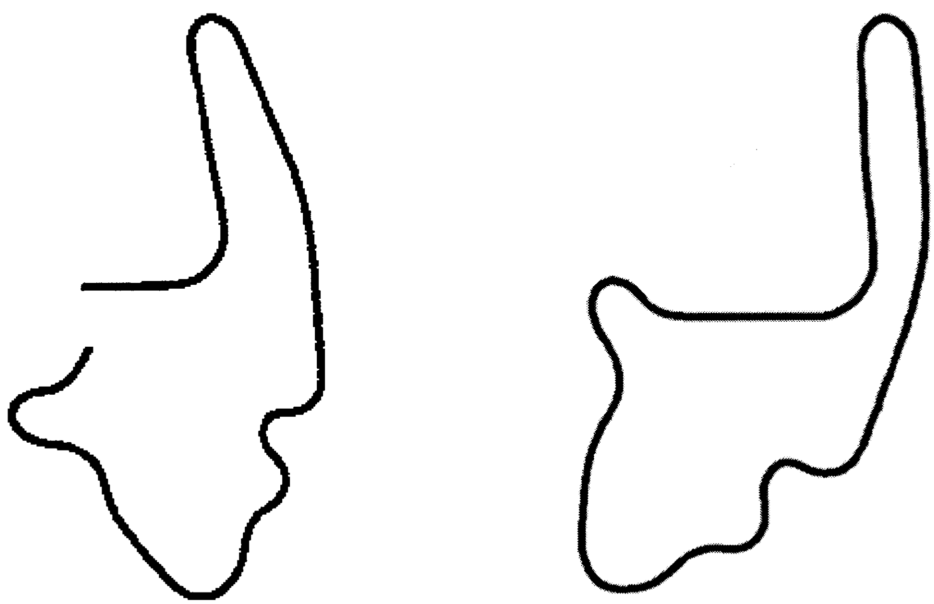
3.1.3.2 End Point Matching

The map is created as described above and the accelerometer correction is applied. To force a match, a small adjustment is made to each of the points in the map. This adjustment is made such that the start and end points match. The difference between the start and end coordinates of the map divided by the number of points gives the correct adjustment. For example, if the end is 10m above the start and there are 1000 data points, then each point must be adjusted by 0.01m. This adjustment is added to each point, and because the points build on each other, the first point is moved down 0.01m, but the second moves down 0.02m. By the end, the last point is moved down the full 10m. The same process is applied again in the perpendicular direction.

$$X_{adj} = \frac{X_N - X_0}{N} \qquad X_i^{new} = X_i^{old} + X_{adj} \cdot i$$

$$Y_{adj} = \frac{Y_N - Y_0}{N} \qquad Y_i^{new} = Y_i^{old} + Y_{adj} \cdot i$$

Figure 3.3 shows a raw map and a map with the accelerometer offset and the end point matching algorithms applied.



Before Accelerometer Correction and End Point Matching

After Accelerometer Correction and End Point Matching

Figure 3.3

3.1.3.3 Remaining Errors

Even after both of these algorithms have been applied, errors still remain. Figure 3.4 shows five maps, from five different cars overlaid on each other.

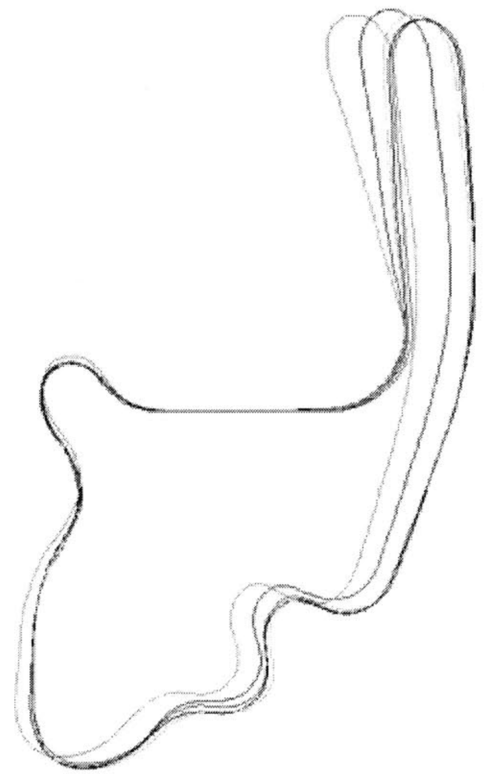


Figure 3.4

Clearly there are major differences. The maps have been lined up at the start point, but by the hairpin turn at the top of the map, the paths are no longer lined up. The radius of the turn is about 50m, which means the path that is farthest to the left is off by about 100m.

So even after extensive correction, the errors that remain are so large that the map is good for visual reference only. These maps are of little use for investigating differences in the driving line. Section 3.3 describes alternative techniques that may be used.

3.1.4 Marking Segments

Track segmenting requires that the start and end of each segment be marked so they can be used to analyze the data from other laps. A method of determining where the car is located on the track is needed.

One method is to use the distance traveled, as measured by the wheelspeed sensor. Unfortunately this method presents some difficulties. Wheelspeed sensors are prone to a number of errors, as described in Section 3.1.2, namely slipping and lock-up. Moreover differences in the driving line may cause one car to travel farther than another. All together, these errors can cause the total distance traveled per lap to vary greatly from lap to lap and car to car.

Although distance is difficult to measure accurately, time is not. The data acquisition system senses the inferred beacon at the starting line and starts the timer for the lap and stops when it crosses the line again. This is a very accurate process and is repeatable within hundredths of a second.

To accurately compare the location on the track of two cars, the percentage of lap time completed can be used. Suppose one car completes the circuit in 84 seconds, and the other in 80 seconds. If the start of a turn is at the 25% mark, then the first car will pass it at 21 seconds and the other at 20 seconds. This works well when the lap times are fairly similar, and the speeds of the cars are fairly similar at all points on the track. Generally, data is compared between similar cars in similar conditions, so overall this method works reasonably well.

3.2 GPS

The Global Positioning System (GPS) is a network of satellites created by the U.S. military. Position on the earth is calculated by triangulating the distance between the satellites. The accuracy of the GPS is a typically within 20m. More accurate forms of GPS, such as differential GPS (DGPS) and carrier-phase GPS can increase the accuracy considerably, down to within a few centimeters.

Carrier-phase GPS measures the Doppler shift in the carrier signal from the satellite, to determine velocity. The velocity is then integrated to determine change in position. The velocity measurements are accurate enough to provide very good position measurements, even after integration.

3.2.1 Map Creation

Making a track map with a GPS system is a straightforward process. With the system installed on the car, the driver simply drives around the track. This will give an outline of the track shape similar to inertial mapping, however it is far more accurate.

The accuracy is high enough to easily distinguish the outside edge of the track from the inside. This allows the boundaries of the track to be located directly. The best method is to attach the GPS antenna to the right side of the racecar then have the driver drive around the right edge of the track. The antenna is moved to the left side of the car and the process is repeated on the left side of the track. Figure 3.5 shows the result.

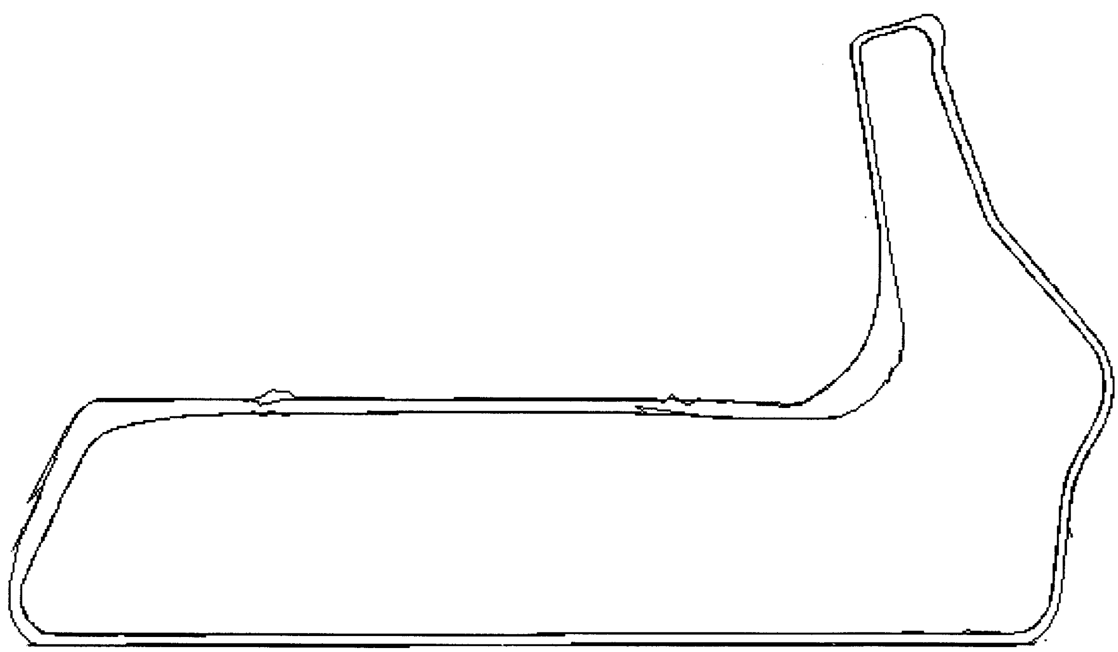


Figure 3.5

Both the inside and outside edge of the track are shown. There are a number of rough locations due to bridges over the track that obstructs the view of the satellites. Once the track map has been made, the position of the car can be overlaid on top. Figure 3.6 shows several laps of data overlaid on the map from above.

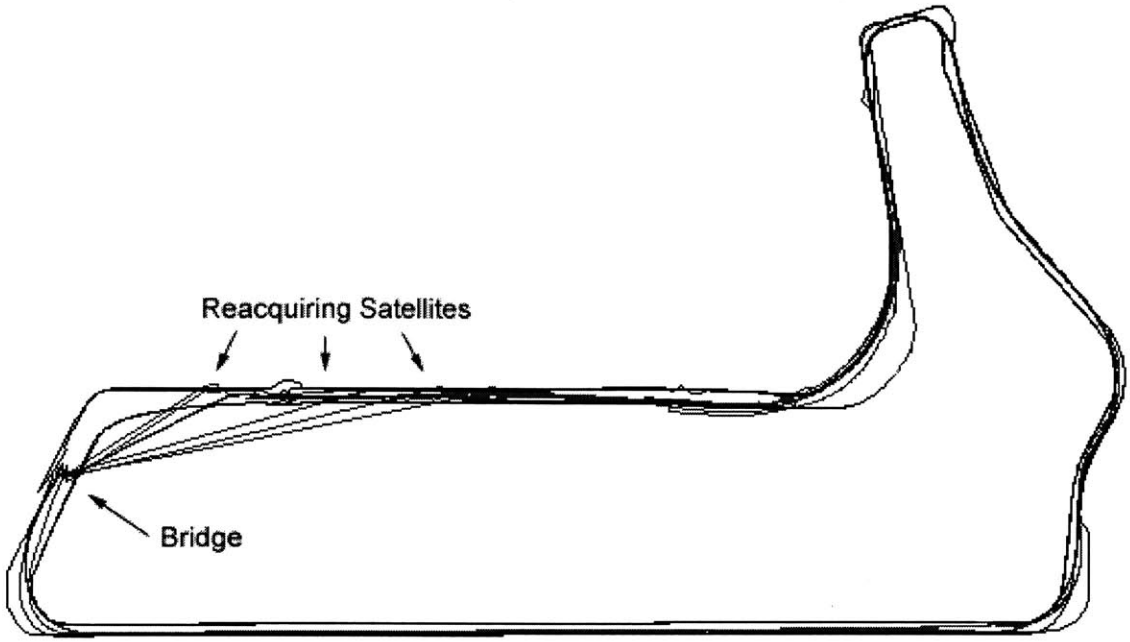


Figure 3.6

The driving lines from all the laps fall within the boundaries of the track. Again under the bridge, contact with satellites is lost. However because the car is now moving much faster, the location where the GPS system reacquires the satellites is much farther down the track. Figure 3.7 shows one of the turns up close.

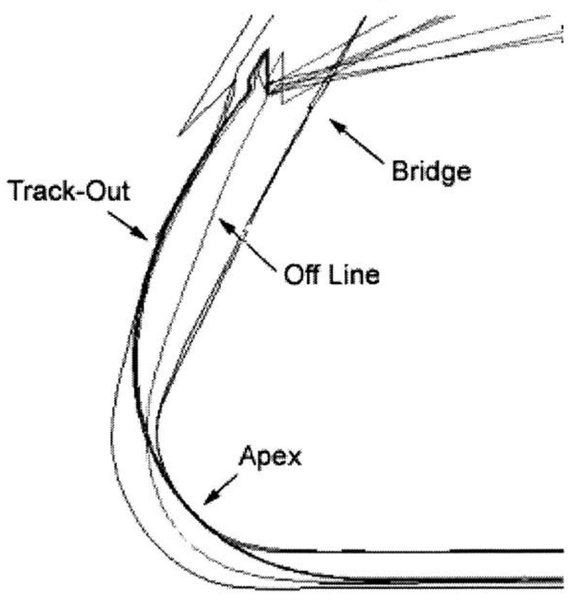


Figure 3.7

The driving line is clearly shown on the track. It overlaps the inside of the track at the apex and extends out to the outside of the track at the track-out point. The driver was also asked to make a lap off the correct driving line. This is also clearly visible.

For comparison, the results of the GPS system is overlaid with the inertial mapping result for data on the same lap. Figure 3.8 shows the result.

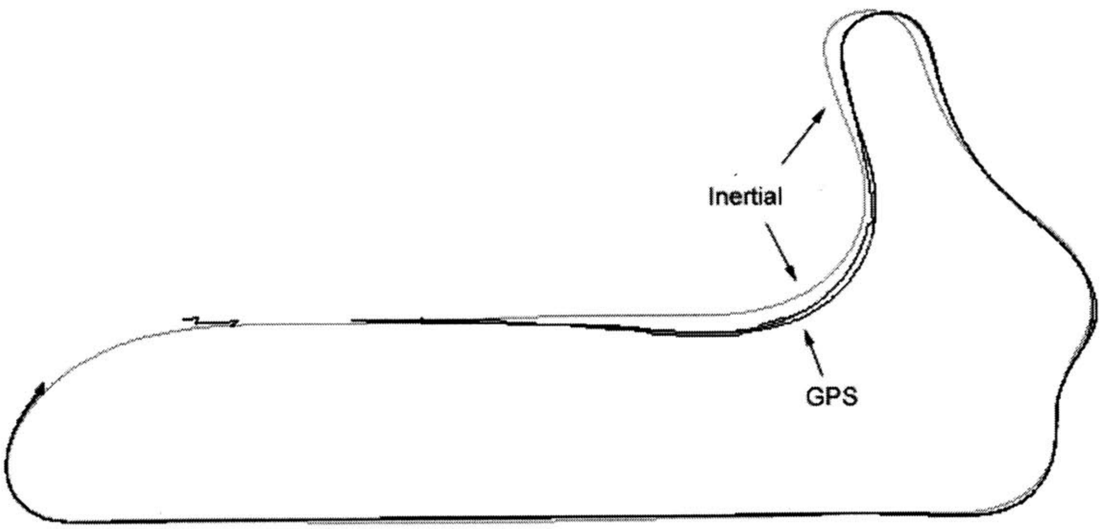


Figure 3.8

The two maps line up fairly well, but it is clear that they do not completely overlap. Also important is that the inertial map is unaffected by bridges or other occlusions.

3.2.2 Errors

The primary error encountered with GPS systems is occlusion, obstructing the view of the satellites. No data is taken while the system is reacquiring satellites. The most common occlusions on a racetracks are trees and especially bridges.

3.2.3 Error Correction

There are several things that can be done to correct occlusion errors. The first is to prevent them from happening in the first place. A ground-based "pseudolites" can be placed near the bridge to improve coverage. If this is not possible, then the data must be corrected.

One way of correcting the data is to combine the GPS data with the speed and lateral acceleration measured on the car. Using the inertial mapping algorithm between the loss of contact and the reacquisition point can fill the holes created when GPS system loses contact with the satellites.

3.2.4 Marking Segments

Segment finding and marking can be done using the GPS information. The GPS system records the speed of the car directly. Segment finding also requires the instant turn radius, which can be found from the GPS position information.

To mark the segments, neither the distance nor the time needs to be used. Instead, the position of the event can be marked, turn-in, etc. Then a line can be drawn perpendicular to the path of the car at that point. This creates a "virtual beacon". When looking at data from other cars, the virtual beacons define the segments. Figure 3.9 shows virtual beacons.

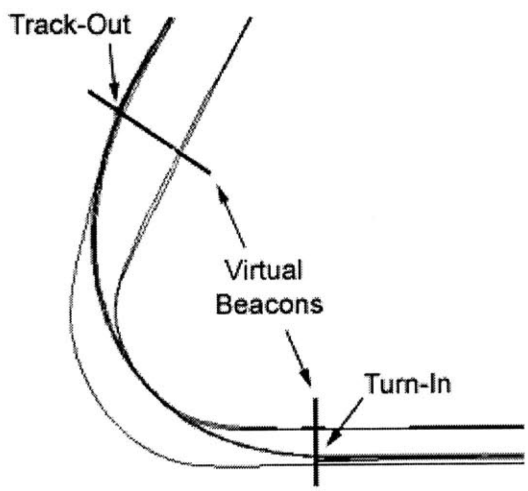


Figure 3.9

3.3 Displaying Drive Line Information

As shown in Section 3.1 inertial mapping systems have inherent problems that prevent them from being useful in driving line analysis. Even though these difficulties exist, that does not mean that no data about the driving line is available. The instant turn radius contains information about the driving line.

3.3.1 *Instant Turn Radius*

The instant turning radius is the radius that the car is traveling about at any given moment. When going straight, the instant turn radius is infinite. When driving around in a circle, the instant turn radius is the radius of the circle. The instant turn radius is not measured directly, but it can be calculated from the speed and lateral acceleration. Physics says that instant radius is equal to the square of the velocity divided by the lateral acceleration.

$$r = \frac{v^2}{a}$$

The accuracy of the instant radius calculation is a function the accuracy in the measurements of the speed and lateral acceleration. The accelerometer correction algorithm from above can be used to adjust the accelerometer data to improve its accuracy. Unlike creating a track map, there is no error accumulation. Because the instant radius is calculated independently for each point, any bad data points at a particular location do not corrupt the calculation at other parts of the track.

The instant radius gives information about what the car was doing at a particular moment, but cannot show the location of the car on the track. Inspecting instant radius information can yield important information.

3.3.2 *Plotting*

The most obvious way to display instant radius information is to plot it on a graph. Unfortunately, because the instant radius is infinite when going straight, it is very inconvenient to plot on a graph. Instead the inverse of the instant radius, called curvature, is used. Curvature is a measure of how much curve a path has at a particular point. Low curvature means little turning, the car is going straight. High curvature means a lot of turning, the same as a small radius. Figure 3.10 is a graph of curvature for two different cars through the same corner.

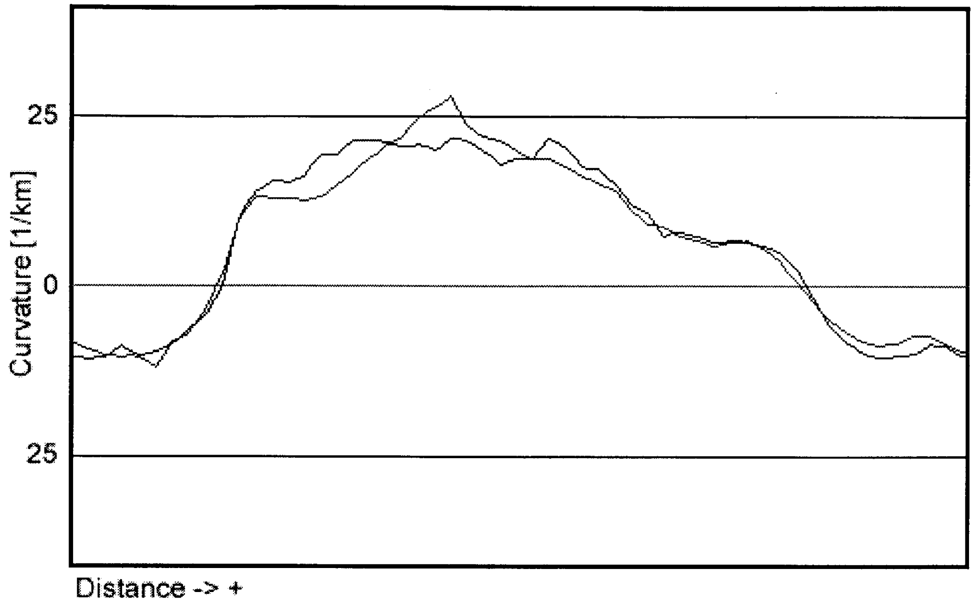


Figure 3.10

The two plots have different shapes. One builds to a point then declines, while the other builds more quickly, but stops at a lower level and then declines similar to the first. This shows the two different approaches the drivers took to the corner. One driver made a sharper turn in the middle while the other kept a more constant radius through the middle.

Plotting depicts differences in the driving line, but is difficult to interpret. It does not give an intuitive feel for what was going on inside the car.

3.3.3 *Path Coloring*

Another method of displaying the instant radius is to draw the section of track and then use color to represent the instant radius. Figure 3.11 shows the same data as above represented in color along the track.

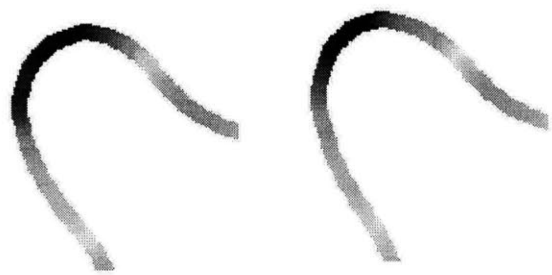


Figure 3.11

The distribution of color shows the instant radius at that point. The first track shows the radius tightening in earlier to a constant amount and holding through the turn. The second plot shows the radius tightening in later to a tighter minimum, and then relaxing out.

This method gives a more intuitive look at path curvature. One difficultly however, is that two laps cannot be overlaid, they must be shown side by side.

3.3.4 Path Marking

Most drivers think of each turn as having three defining points: turn-in, apex and track-out. Another method of displaying driving line information is to mark these points along the track. Figure 3.12 shows the same data as above, but also has the turn-in, apex and track-out points marked.

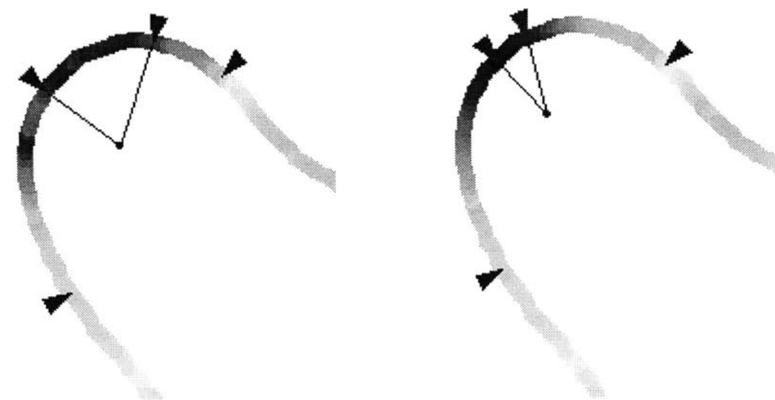


Figure 3.12

The apex markings show where the instant radius is within 10% of the local minimum. This gives an indication of the length of the apex, whether the car took a set and held it through the corner or it shot down to the apex and then shot back out. The path markings for several cars may overlaid on the same track for easy comparison.

4 Example

This section shows an example of how this software would be used in a racing situation. The performance of two drivers, Bobby and Adam, is compared on the street course in Vancouver, British Columbia. Bobby was the fastest driver of the session with a time of 76.34 seconds. Adam is slower at 76.86 seconds and needs to identify where he can make up time.

The most important turn in any racetrack is the one before the longest straightaway. At Vancouver the longest straight is the back straight. Turn 5 leads on to the back straight, however it is large enough radius that the driver does not have to lift from the throttle. This effectively makes Turn 3 lead on to the back straight and is therefore the most critical. Figure 4.1 shows a screen shot of the DataWizard program with the turns identified.

Because Turn 3 is the most important, it is a good starting point when looking for places to make up time. The user then selects "Tn 3" from the list on the left to see the details.

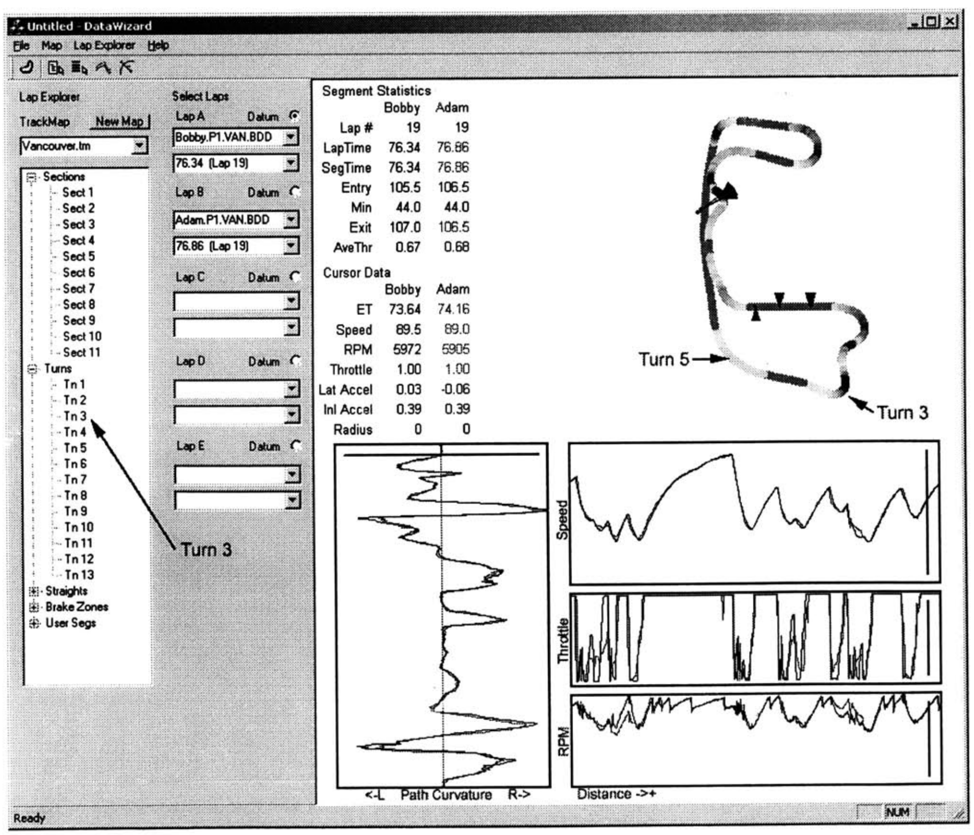


Figure 4.1

Figure 4.2 is a screen shot of the DataWizard program after Turn 3 has been selected. The map and plots have zoomed in on Turn 3 and a list of Segment Statistics ha been generated.

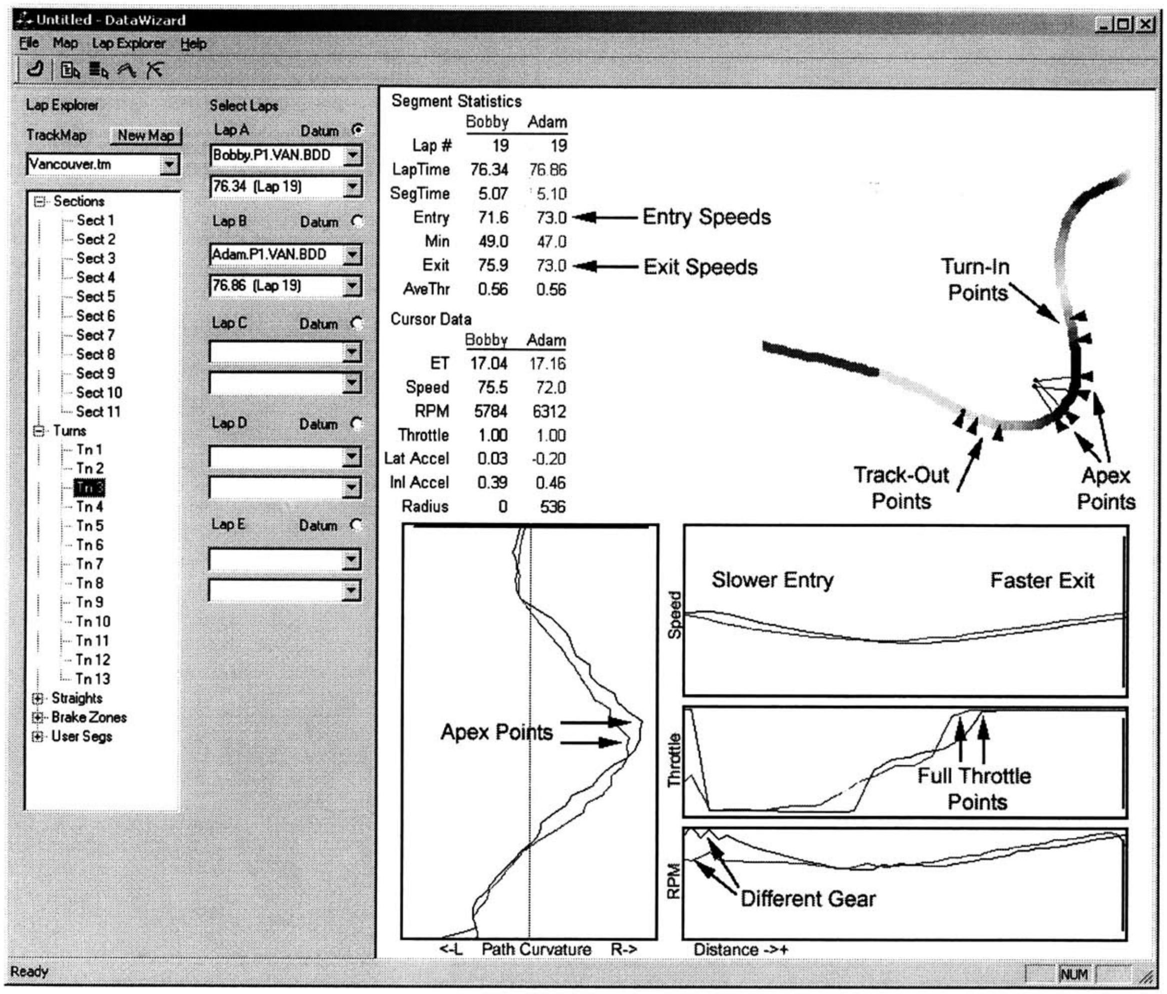


Figure 4.2

The first thing to inspect is the speeds in the Segment Statistics. Bobby is exiting Turn 3 at 75.9 mph while Adam is exiting at 73.0 mph. This is a significant speed difference and considering the length of the following straight, it will have a large effect on lap time. Next, notice that Adam is actually faster on entry to the corner, 73.0 mph compared to Bobby's 71.6 mph. This seems to indicate that Adam is too aggressive on corner entry, and is hurting exit speed.

The Path Curvature plot shows that Bobby apexes earlier in the corner than Adam. This earlier apex also allows Bobby to reach full throttle sooner, as shown in the Throttle plot. Bobby is also using a higher gear (lower RPM's) through the previous corner (Turn 2), which can limit the available power and may be helping to keep the car more settled for Turn 3. The difference in apex position is also seen in the corner markings on the map. Also shown is the difference in position of the turn-in and track-out points.

5 Summery & Conclusions

Effective use of data is an important part of increasing driver-vehicle performance. Drivers, coaches and engineers must be able to quickly interpret and utilize car data in order to improve vehicle performance. The data analysis software must facilitate, or act as a catalyst in this process. The data analysis software should help move data from being just a set of *numbers* to being useful *information* or *knowledge*.

Track segmenting forms a good framework for organizing and summarizing data. Track segmenting is an organization structure that allows the user to navigate through the data in a manner that parallels the way the driver thinks about the course. This parallel give an intuitive system of organization that is clear and easy to understand. Core information from each segment can be found and displayed to the user as a list of statistics relevant to that segment. Again these statistics are designed to give the driver easy access to data that reflects on track performance.

Driving line is important, but is challenging to accurately extract from data. The correct driving line is the first step to driving faster. Ideally the data would contain accurate data about where the car was on the track at each instant. Unfortunately, the inertial mapping systems that are commonly used are unable to provide the required accuracy, even after attempts to correct the data. GPS systems measure position directly via satellites and may prove to be useful tool in recording the driving line. However GPS is only beginning to be applied in racecar applications, and it is unclear if other issues will prevent its widespread use.

Although driving line cannot be measured directly, using instant turn radius or path curvature data can provide useful insight into driver-vehicle performance. The instant turn radius is calculated independently at each point along the track and is not prone to the same integration errors as in inertial mapping. The instant radius is useful, however it can be hard to interpret from a plot. Other methods of displaying the instant radius such as using color along a track map, or marking turn-in, apex and track-out points on a track map give a better more intuitive way of viewing the information.