

# Testing and Tuning a Formula SAE Racecar



Dartmouth Formula Racing

**ENGS 199:** Hybrid Vehicle Technology

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# Testing and Tuning a Formula SAE Racecar

This paper presents a framework for testing and tuning a Formula SAE Racecar. Through a decade of race engineering, Dartmouth Formula Racing has found that effective testing and tuning is essential for achieving peak vehicle performance. Success on the track requires both a thorough understanding of vehicle dynamics and an efficient and robust method of data collection and management. Here, we introduce basic concepts of vehicle dynamics and suggest one possible system for data collection and management.

## Dynamic Tuning

Dynamic adjustments involve all modifications to the car that affect the distribution of power among the four wheels. These modifications can be grouped into three categories: wheel geometry, suspension damping, and powertrain. A basic description of each dynamic parameter is included in Appendix A. These parameters are intended to describe a racing package similar to Dartmouth Formula Racing's 2006 FSAE car. There may be significant differences in dynamic tuning parameters for different FSAE packages.

### *Wheel Geometry*

The following parameters are commonly used to describe the geometry of each of the car's wheels. In almost all racing applications, the parameters are held constant between left and right wheels, though they are often different between front and rear.

- Ride Heights
- Camber
- Caster
- Ackerman
- Toe

### *Suspension Damping*

Suspension damping is the car's ability to control the vertical oscillations of the wheels. By altering the car's shocks, springs, and anti-roll bars, it is possible to manipulate the

behavior of the car under lateral acceleration. It may also be possible to implement anti-heave or anti-pitch bars to control the car's behavior under longitudinal acceleration.

- Shocks
- Springs
- ARB's

### *Powertrain*

The last component of dynamic tuning is adjustment of the powertrain to control distribution of power under acceleration and braking.

- Drive Ratio
- Brake Bias

## Data Collection

Successful dynamic tuning requires both a thorough understanding of the various dynamic parameters and sufficient data to justify any modifications. Given the relative ease with which data can be collected, it is imperative to monitor the car's behavior precisely and consistently. Effective data collection and management is accomplished through both an onboard data acquisition system and designer observation.

### *Data Acquisition System*

The key functionality of any onboard data acquisition system is to be able to record real-time data of multiple vehicle parameters. Depending upon the team's design goals, these parameters may be very different. Whatever the parameters, the data acquisition system should allow designers to observe changes in vehicle behavior and track interactions between system variables. Typical data acquisition components are listed below:

- Global Positioning System
- Lateral and longitudinal accelerometers
- 4x wheel speed sensors
- 4x rotor temperature sensors
- 4x linear position sensors
- Manifold air pressure
- Manifold air temperature
- Coolant temperature
- Brake pressure
- Throttle position sensor
- Steering wheel position sensor

- Gear position sensor
- Oil pressure

Typical data acquisition systems will sample these parameters at high frequency (20-100 Hz) and store the data on a flash memory card. Advanced functionality includes communication of key parameters with a driver display and wireless transmission of data for real time pit monitoring. It may also be possible for the data acquisition system to receive data wirelessly and adjust system parameters (such as engine fuel maps) on the fly.

Perhaps the most critical feature of a successful data acquisition system is an effective data management tool. This software should enable designers to track interactions between multiple parameters and compare data between different driving sessions. For instance, one might want to observe the changes in engine speed and manifold pressure during an acceleration run. In addition, it should be possible to overlay front wheel speed and rear wheel speed during several acceleration runs with different gear ratios in order to determine the amount of wheel spin under each setup. Further, one might want to observe course position and speed on an endurance event for several drivers in order to compare driving strategies such as corner entry and exit. Only a sophisticated data management tool will allow designers to observe data in meaningful ways.

Dartmouth Formula Racing's current system is the DL2 Data Logger by Race-Technology.com paired with RT Analysis software, also distributed by Race-Tech. Refer to Appendix B for a description of this data management tool.

### *External Data Collection*

When it is not possible for the data acquisition system to collect certain data or when it is desirable to have duplicate data, external data collection may be employed. One important form of external data collection is static setups, which record all relevant vehicle settings such as those discussed earlier in this paper. By recording these setup parameters, one may directly observe the changes in vehicle performance under different setups.

In addition to static data, it may be desirable to record dynamic parameters. Recording lap times helps to correlate data with data acquisition system since start and stop points are often hard to identify. In addition, tire temperatures and pressures are difficult to monitor using the onboard data collection system. Perhaps the most useful and important form of external data collection is driver feedback. By using driver feedback to identify problems with the car's current setup, designers can be more effective in analyzing dynamic data and making appropriate adjustments.

As with the data acquisition system, an effective data management tool is necessary in order to make good use of externally-recorded data. The software used to track external data should be able to interact seamlessly with the onboard data management tool. Dartmouth Formula Racing's current solution is very limited and should be expanded in the future to allow for more sophisticated data manipulation. Refer to Appendix C for a description of the functionality of the current data management system and recommendations for future improvements.

## Design Modifications: The Continuous Function Approach

One effective strategy for tuning a Formula SAE racecar is the "continuous function approach." Based on the assumption that all of the car's dynamic properties act as continuous functions of many parameters, the goal is to tune the car to operate at both extremes of the desired performance. If it is possible to achieve both extremes under different static setups, then it must be possible to tune the car for optimal performance using some combination of the extreme setups.

The obvious example of this strategy is cornering behavior. By loosening the rear shocks and using a stiff ARB, we were able to achieve gross understeer on both corner entry and corner exit. We then removed the rear ARB entirely and hardened the rear shocks to achieve considerable oversteer. This helped to confirm the effect of altering the relative hardness of front and rear shocks ARB rigidity.

Another example of the continuous function approach is the selection of a final gear ratio. During the first days of testing, we found that our final gear ratio of 3.89 was too high and resulted in considerable wheel spin under acceleration. We replaced the front and rear sprockets to yield a gear ratio of 3.33, which we anticipated would be too low. This was confirmed during testing as the car felt sluggish during acceleration launches, and it was not possible to spin the rear wheels. The drive ratio used in competition was 3.58, which gave drivers the ability to push the rear tires just beyond their tractive limit.

The continuous function approach is also useful in identifying the car's limits. During testing on a high speed track, we identified excessive body roll as a major concern. Despite making many modifications to the car's springs, shocks, and ARBs, we were not able to prevent the inside rear wheel from lifting during high speed turns. This is a significant issue because the car's differential is only able to distribute power to the road when both rear wheels can maintain some traction. Ideally, the car should see no more than 80% lateral weight transfer. Due to the car's relatively high center of mass, we were limited to 1.8g lateral acceleration before completely unloading the inside wheels. The continuous function approach helped the team to quickly identify body roll and weight transfer as an issue and spurred an analytical investigation into the causes of our tuning limitations.

As an academic approach, the continuous function method is far from elegant. However, as a tuning strategy, it allows design teams to test the limits of their tuning ability and quickly develop an understanding of how setup modifications affect the car's dynamic behavior. Further, it helps build a robust data set, which describes the car's full adjustment range. The continuous function approach paired with extensive data collection will help student design teams develop a complete model for their car's dynamic behavior and achieve peak driving performance.

## Appendix A: Dynamic Parameters

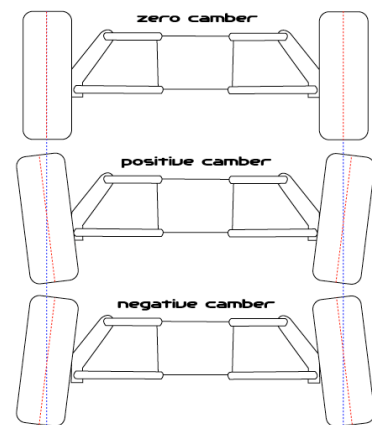
## Wheel Geometry

### Ride Height

Ride heights are measured for the front and rear of the car from any constant inboard reference point, typically the lowest point on the frame. By tracking these ride heights (in inches), it is possible to determine two key parameters. First, the difference in ride heights describes the car's neutral pitch angle, or rake. Second, a net change in ride heights changes the car's center of mass.

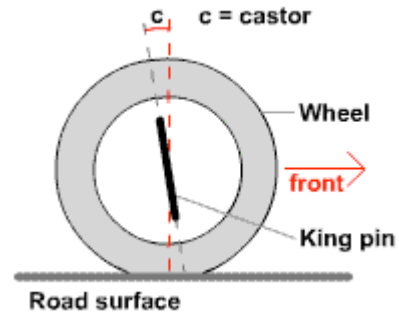
### Camber

Camber describes the vertical inclination of each wheel. Measured in degrees from a vertical line, positive camber indicates the wheel leans away from the car's centerline, and negative camber indicates the wheel leans toward the car's centerline. Camber is typically measured with a vertical level.



### Caster

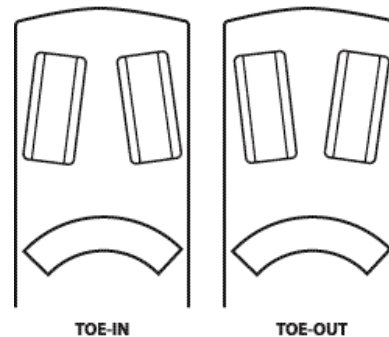
Caster is the angle between the axis of rotation of the front upright and a vertical line. Negative caster indicates the axis of rotation is declined toward the car's center. Caster is difficult to measure and is most often determined using 3D modeling software for different suspension settings.



### Toe

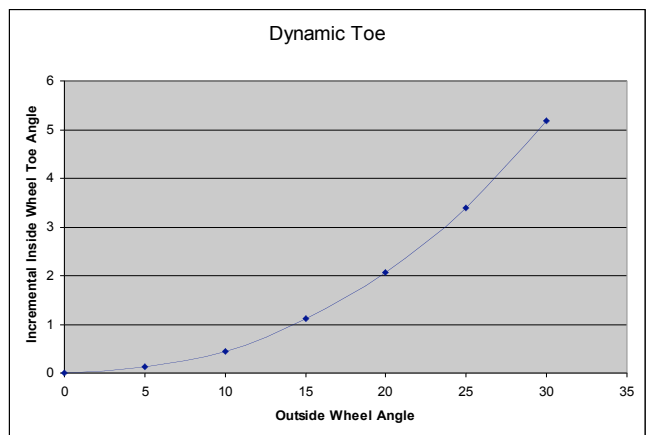
Toe is a measure of the wheel angle relative to the car's intended direction. Toe-in indicates that wheels are pointed toward the car's centerline, and toe-out indicates that the wheels are pointed away from the car's centerline. Despite the fact that toe is an angle, it is typically measured in inches using a toe rectangle (image below). By

measuring the distance of the wheel's front edge from the toe rectangle, it is possible to track toe settings.



## Ackerman

Ackerman describes the difference in steering angles between inside and outside wheels. It is also referred as dynamic toe. There is no convention for describing the amount of Ackerman in a steering system. Dartmouth Formula Racing has referred to Ackerman settings as full, mid, and min to describe the difference in steering angles since the degree difference varies with steering wheel angle. See below for a graph that illustrates dynamic toe.



## Suspension Damping

### Shocks

In order to achieve optimal damping properties, shocks should be tuned to achieve the desired damping coefficient under four loading scenarios: high speed compression, low speed compression, high speed rebound, and low speed

	High Speed	Low Speed
Compression		
Rebound		



rebound. Typically, damping coefficients are held constant between left and right wheels but may be different front to back.

### Springs

Springs are generally purchased off the shelf and offer no tuning ability. Instead, many different spring with different spring coefficients may be swapped in and out of the spring/shock system to alter wheel response to bump and roll. Typically, spring coefficients are held constant between left and right wheels but may be different front to back.

### Anti-Roll Bars

Anti-roll bars (also known as sway bars) limit the difference between left and right shock/spring positions. ARB settings are measured as torsional rigidity, which may be determined by the moment arm over which roll torque is transferred or by the cross-sectional area of the ARB.

### Powertrain

#### Drive Ratio

The final drive ratio is determined by dividing the number of teeth in the drivetrain sprocket by the number of teeth in the engine's output shaft sprocket. A high gear ratio yields a high step-up in torque from the engine to the drivetrain and results in quick engine speed increases and rapid shifting. A low gear ratio, or "tall final drive," results in lower drivetrain torque, longer time in each gear, and higher maximum vehicle speed.

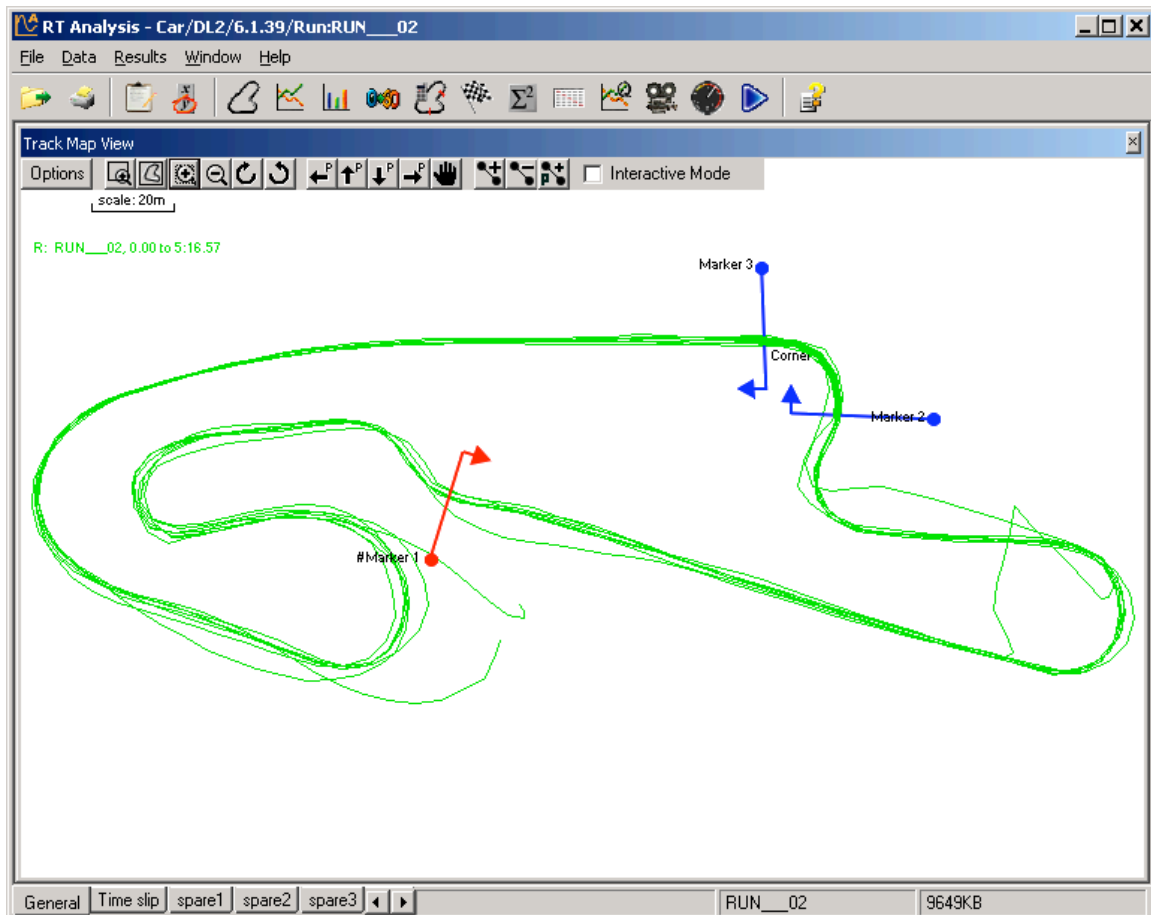
### Brake Bias

Brake bias measures the relative braking effort distributed between front and rear wheels. By recording the number of turns on the brake bias bar, it is possible to track the relative front-to-rear brake bias.

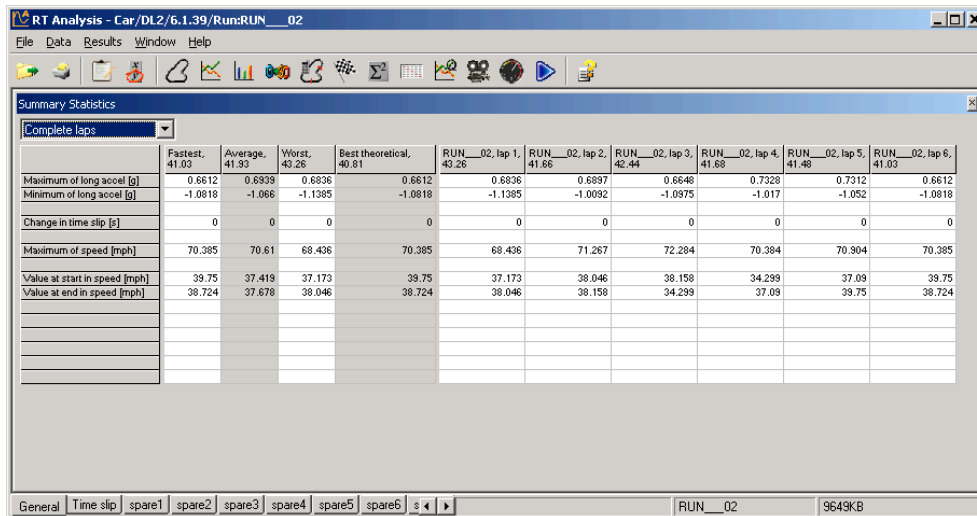
## Appendix B: Data Acquisition Software

Dartmouth Formula Racing uses RT Analysis software, authored and distributed by Race-Technology.com. The software allows users to import raw data from any Race-Tech data acquisition system and analyze vehicle parameters using both text-based and graphical methods.

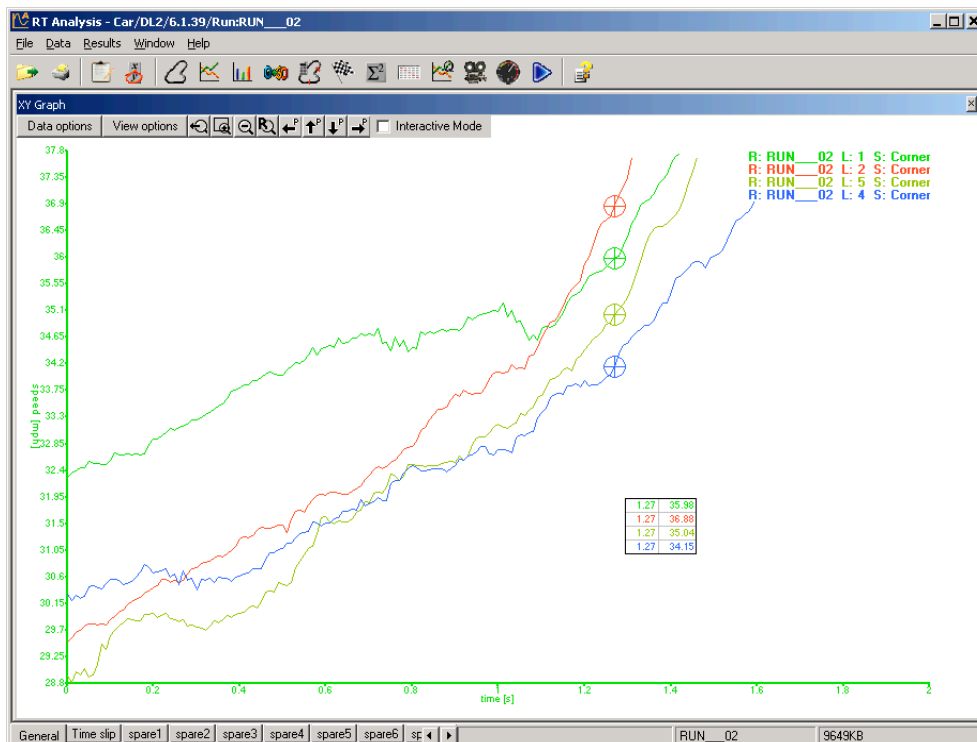
Users are able to partition data into runs. Each run is then automatically subdivided into laps and sectors, based on user preferences. The first graphical display is a track map, which illustrates the path followed by the car. Here, users are able to specify the “start” position and also create markers throughout the course. These markers determine the points at which the runs are subdivided. For instance, the data points that lie between Marker 2 and Marker 3 are grouped into a sector called “Corner.” This simplifies data organization, as illustrated in the following example.



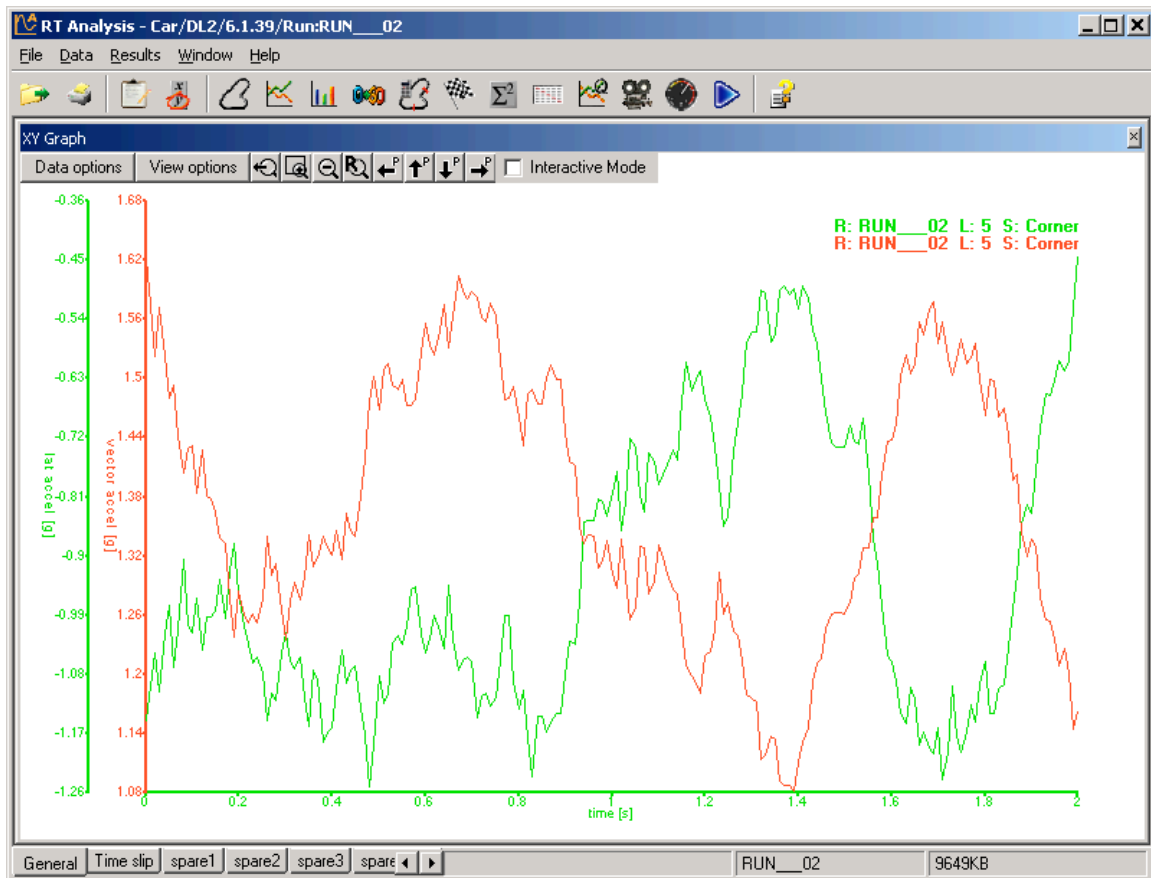
Once a run has been subdivided, users can view track data for each sector of the course. The RT Analysis software generates basic statistics, such as lap and sector times, speeds, and acceleration.



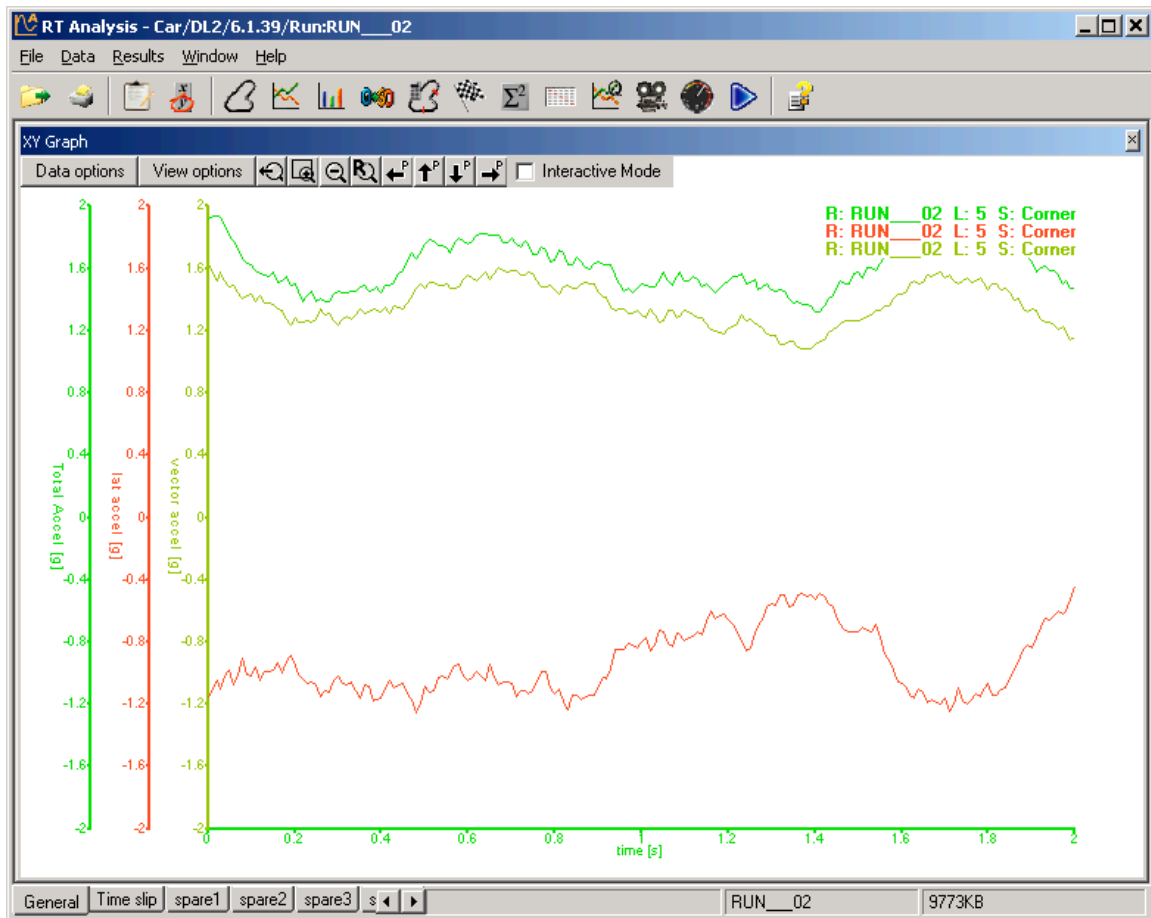
Users can also request more customized data presentation using the “XY Graph” feature. For instance, users can request a graph that plots vehicle speed versus time through the “Corner” sector of laps 1 through 4 (shown below).



In addition, users can plot multiple parameters from a single lap to compare interactions between parameters. For instance, the plot below shows lateral and longitudinal accelerations through the “Corner” sector of lap 2. Note the apparent tradeoff between lateral and longitudinal acceleration. This suggests that the driver may feel the tires approaching their tractive limit during the turn.



To explore this possibility further, users can define custom variables, such as the net acceleration (sum of squares of longitudinal and lateral accelerations). This new parameter can also be plotted with the base parameters as shown below. The net acceleration plot (in green) shows that the total vehicle acceleration varies through the turn, with a maximum at the predicted tractive limit of 1.8 g's.



This example serves purely to illustrate the features of a successful data management software package. It is clear, however, that such functionality allows racing teams to quickly and easily draw meaningful information from complex data sets.

## Appendix C: Track Data

Dartmouth Formula Racing's current track data management system allows for basic data input and searching. Run as a plug-in to Microsoft Excel, the tool provides users with a simple interface for inputting track data and another similar interface for retrieving historical data.

**Static Setup**

Setup ID: 5/4/2006-3  
Date: 5/4/2006  
Time: 1:30:00 PM  
Location: Timken  
Air Temp: 65  
Weather: P Cloudy  
Car: Candi  
Driver: Schaut  
Engineer: Kane  
Front Rotors: Competition  
Rear Rotors: Standard  
Brake Bias: 3.5  
Front Shocks: 0  
Front Springs: 130  
Front ARB: 0.3125  
Rear Shocks: 3  
Rear Springs: 90  
Rear ARB: 0.3125  
Camber: LF -1, RF -1.5, LR -1.3, RR -0.8  
Caster: LF -4, RF -4, LR -0.7, RR -0.7  
Ackerman: Full  
Front Toe: 0.03  
Rear Toe: 0.06  
Ride Heights: LF 2.6, RF 2.625, LR 3.25, RR 3.25  
Gear Ratio: 3.33  
Map File: Candi\_050406  
Wastegate: Full  
Tires: Hoosier  
Comments: Looser rear springs

**Dynamic Data**

Course Type: Autocross  
Times: 1 38.24, 2 37.34, 3 37.24, 4 37.75, 5 37.54  
Tire Temps: O M I I M O, 117 132 124 121 130 112, O M I I M O, 141 172 163 141 154 131  
Tire Pressure: LF 11, RF 11, LR 12, RR 12  
Comments: 1,4 (cone)

Data is broken into “Static Setups” and “Dyanmic Data.” Each set of dynamic data references the static setup under which the data was collected. Since new setups are often incremental changes of a small number of parameters, the “Retrieve Last” button loads

all parameters of the last static setup. In addition, users should employ the “New Setup” button to automatically load the time and date and generate a new setup ID. This ensures that all setup IDs are unique and that track data is filed properly. Conventions for data collection are explained in the “Conventions” sheet, which is included at the end of this appendix.

The screenshot shows the Microsoft Excel - Track\_Data window. The interface is divided into three main sections: Static Setup, Dynamic Data, and Matches.

**Static Setup:** This section contains a list of parameters for a race setup, including Setup ID, Date, Time, Location, Air Temp, Weather, Car, Driver, Engineer, Front Rotors, Rear Rotors, Brake Bias, Front Shocks, Front Springs, Front ARB, Rear Shocks, Rear Springs, Rear ARB, Camber, LF, RF, LR, RR, Caster, LF, RF, LR, RR, Ackerman, Front Toe, Rear Toe, Ride Heights, LF, RF, LR, RR, Gear Ratio, Map File, Wastegate, Tires (Hoosier), and Comments. A "Get Last Setup" button is located at the bottom of this section.

**Dynamic Data:** This section contains a "Load Data" button, a "Setup ID" field, a "Course Type" field, a "Times" table (1-15), a "Tire Temps" table (O, M, I, I, M, O), and a "Tire Pressure" table (LF, RF, LR, RR).

**Matches:** This section displays a list of matches, showing Setup ID and Course Type. The matches listed are:

Setup ID	Course Type
4/9/2006-1	
4/9/2006-2	
4/9/2006-3	
5/4/2006-1	
5/4/2006-1	Autocross
5/4/2006-2	
5/4/2006-2	Autocross
5/4/2006-2	Autocross1
5/4/2006-2	Autocross2
5/4/2006-2	Autocross3
5/4/2006-2	Autocross4
5/4/2006-3	
5/4/2006-3	Autocross
5/4/2006-3	Autocross1

Under the “Get Data” tab, users are able to search historic data using static setup parameters. Matches are displayed to the right of the sheet and are displayed as static setup IDs and course types for setups with dynamic data. The example above lists all

track data for which Nick Schaut was driving Candi with full hard front shocks, full loose rear shocks, and Hoosier tires.

Users are then able to input any of the matches into the Dynamic Data box. By clicking “Load Data,” all fields in both the Static Setup and Dynamic Data boxes are loaded with the requested data. The image below shows the results of this process for Setup ID “5/4/2006-2” and Course Type “Autocross.”

The screenshot shows a Microsoft Excel spreadsheet titled "Track\_Data" with two main data entry areas: "Static Setup" and "Dynamic Data".

**Static Setup:**

- Setup ID: 5/4/2006-2
- Date: 5/4/2006
- Time: 11:00:00 AM
- Location: Timken
- Air Temp: 65
- Weather: Sunny
- Car: Candi
- Driver: Schaut
- Engineer: Hodgson
- Front Rotors: Competition
- Rear Rotors: Standard
- Brake Bias: 3.5
- Front Shocks: 0
- Front Springs: 130
- Front ARB: 0.3125
- Rear Shocks: 3
- Rear Springs: 110
- Rear ARB: 0.3125
- Camber: -1
- LF: -1.5
- RF: -1.3
- LR: -0.8
- RR: -0.7
- Caster: -4
- LF: -4
- RF: -0.7
- LR: -0.7
- RR: Full
- Ackerman: 0.03
- Front Toe: 0.06
- Rear Toe: 2.625
- Ride Heights: 2.625
- LF: 3.25
- RF: 3.25
- LR: 3.33
- RR: Candi\_050406
- Map File: Full
- Tires: Hoosier
- Comments: stiffer front sway bar

**Dynamic Data:**

- Setup ID: 5/4/2006-2
- Course Type: Autocross
- Load Data button
- Times table:

Times	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	38.33														
2	37.87														
3	37.26														
4	38														
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															

**Tire Temps:**

O	M	I	I	M	O
102	116	111	123	121	110

**Tire Pressure:**

O	M	I	I	M	O
120	141	132	160	161	134

**Matches:**

Setup ID	Course Type
4/9/2006-1	
4/9/2006-2	
4/9/2006-3	
5/4/2006-1	Autocross
5/4/2006-2	Autocross
5/4/2006-2	Autocross1
5/4/2006-2	Autocross2
5/4/2006-2	Autocross3
5/4/2006-2	Autocross4
5/4/2006-3	Autocross
5/4/2006-3	Autocross1

Searching within tolerance settings is not yet implemented, but should be considered for future development. In addition, direct integration with the Data Acquisition software



may be a useful feature. Currently, users must match the two data sources manually. This is a manageable process given our familiarity with the car's testing history and the relatively small amount of data. However, automatic data matching could be a very useful feature. Finally, if there is sufficient data, there are some interesting statistical analyses that could lend insight into the car's behavior. For instance, it may be possible to track correlations between static setup parameters and dynamic data. Camber, for instance, should be directly correlated with tire temperature gradients. Given the small amount of data, any covariances found between parameters will be statistically insignificant. A more rigorous data collection process might be able to make use of this sort of analysis.

## Data Storage Conventions:

Microsoft Excel - Track\_Data

File Edit View Insert Format Tools Data Window Help Sensitivity Toolkit

Type a question for help

79%

Arial 10 B I U

T31

Dartmouth Formula Racing  
Track Data: Conversions

**Static Setup**

Setup ID	
Date	
Time	
Location	
Air Temp	Fahrenheit
Weather	Sunny, P Cloudy, M Cloudy, Rain
Car	
Driver	
Engineer	
Front Rotors	Standard, Competition
Rear Rotors	Standard, Competition
Brake Bias	Turns from Full Front
Front Shocks	0 = Full Hard, 3 = Full Soft
Front Springs	
Front ARB	
Rear Shocks	0 = Full Hard, 3 = Full Soft
Rear Springs	
Rear ARB	
Camber	
LF	measured in inches from neutral
RF	
LR	
RR	
Caster	
LF	degrees
RF	
LR	
RR	
Ackerman	Full, Half, Zero
Front Toe	Positive = Toe Out
Rear Toe	Positive = Toe In
Ride Heights	
LF	inches
RF	
LR	
RR	
Gear Ratio	
Map File	
Wastegate	
Tires	
Comments	

**Dynamic Setup**

Course Type Duplicates should be appended with numbers (eg Autocross4)

Times

1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

Tire Temps

O	M	I	I	M	O
Degrees Fahrenheit					
O	M	I	I	M	O

Tire Pressure

LF	
RF	
LR	
RR	

Comments numbers indicate laps with cone or course out, list driver switches here

Input Data / Get Data / Static Setup / Dynamic Data / Conversions

Draw AutoShapes

Ready NUM