Steering Effort Analysis of an Oval Racing Track Setup Champ Car

Author: Skip Essma
Newman Haas Racing

Abstract

A racing driver’s sensory inputs supply visual, tactile, and inertial information used in developing a “feel” for car handling and performance. This feedback is necessary in enabling the driver to extract maximum performance from the racecar. Steering effort is an important feedback mechanism giving the driver information on stability and directional control. This paper discusses methods used in evaluating and modifying steering effort for a CART series Champ Car racing on an oval track.

Introduction

The sport of automobile racing is devoted to extracting the maximum performance from driver, car, and team. Increasing the performance of any one of these elements can enhance the competitive level of a racing team and improve the chances of achieving the ultimate goal of winning races. However, capitalizing on these performance improvements must be achievable to be of use. This relationship is true when describing the driver and racecar interface. The driver must be able to control and exploit racecar performance improvements to affect increases in speed and hence reduction in laptime.

The driver interfaces with the racecar through control inputs and feedback including the steering wheel and pedals, and through visual inputs, such as dashboard readings and shift lights. The driver provides inputs through the steering wheel to provide directional control and maintain stability. Feedback is received through the steering wheel as torques, forces, and vibration. This paper discusses steering wheel torque or “effort” characteristics specific to a Champ Car setup for an oval racing track.

Steering System Design Considerations

Steering system design for passenger cars and racecars has many similarities. Examples include maintaining desirable toe relationships between the steered wheels, supplying sufficient feedback to maintain directional control, and limiting steering effort and vibration to acceptable levels. While the design goals are similar, the weighting of these factors is very different. A typical passenger car steering system design weights driver comfort over steering feedback. This is done for good reason. Passenger cars rarely operate in limit-handling regions where steering feedback is critical for maintaining direction control. This is contrary to the requirement of a racecar to perform in limit-handling regions as much as possible. Because of this, steering effort and vibration isolation is a secondary consideration to steering and suspension geometry, and packaging factors.

Given this weighting, a high level of steering effort can result and cause problems for the driver. If the steering effort is too high, it can affect the driver's ability to control the racecar and can cause fatigue during races. There are obvious methods of reducing steering effort such as using a larger diameter steering wheel, increasing the steering rack ratio, or increasing the steering arm length. However, these are often unsuitable options due to ergonomics and design space constraints. This paper examines effectiveness, advantages, and disadvantages of alternate methods for decreasing steering effort.

Steering Effort Characteristics on an Oval Race Track

In general, the CART series holds Champ Car racing events on two types of circuits: road course tracks and oval tracks. Road course tracks are comprised of both left- and right-hand turns, while oval tracks are comprised of only left-hand turns. Due to turns in both directions, racecars prepared for road course events have basically symmetric setups. However, oval track racecars are optimized for turning in one direction only resulting in asymmetric setups. This asymmetry generates steering effort characteristics that are peculiar to oval tracks and very different from a passenger car driver's experience.

Due to the asymmetry, steering effort while driving in a straight line is typically very high and to the right or clockwise. In other words, while driving down the straight on an oval racing track the driver is maintaining a straight-line trajectory by applying a steering torque toward the outside wall. The steering effort does not become zero until the steering wheel is turned to the left, and the vehicle is producing a lateral acceleration to the left. The sign conventions used in this paper are that a counter-clockwise applied steering wheel torque applied by the driver is positive, and a left-hand turn yields positive lateral acceleration.

This is obviously very different from the characteristics of driving a passenger car. Steering effort is expected to be nominally zero when driving in a straight line and to increase as lateral acceleration increases. In addition, the magnitude of steering wheel torque should be symmetric for left- and right-hand turns. These same symmetric characteristics are found in a Champ Car setup for a road course track.

Figure 1 shows a plot of steering wheel torque, M_{sw}, versus lateral acceleration, a_y, extracted from on-track measured data logged on an oval racing track. Note that the steering wheel torque while driving in a straight-line, i.e. lateral acceleration = 0, is -11 ft-lbs. Steering wheel torque does not become zero until the racecar is producing a 2.3g lateral acceleration. At peak lateral acceleration (approximately 3.7g), the steering wheel torque is 8 ft-lbs. Therefore, the magnitude of steering wheel torque is greater when driving in a straight-line than when cornering at maximum lateral acceleration.

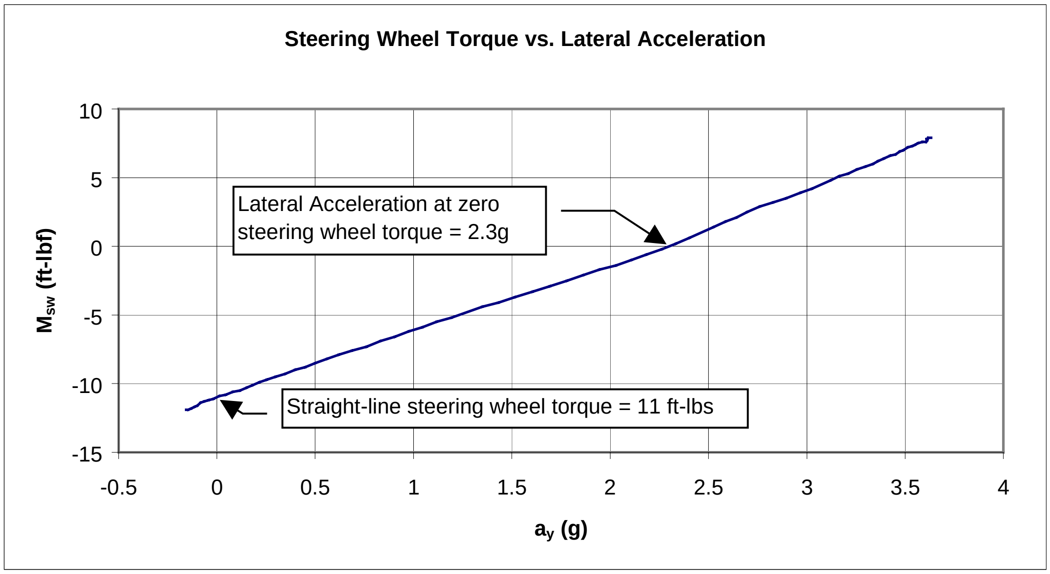

Figure 1: Steering Wheel Torque vs. Lateral Acceleration

Steering Effort Mechanism

As stated above, the steering effort characteristics for an oval racing track setup Champ Car are very different from a symmetric road course car. However, we must identify the mechanism for the asymmetric steering effort in order to improve them. Of the six forces and moments produced at the tire contact patch, this paper will investigate the contributions of lateral force, Fy, and aligning moment, Mz, to steering effort. The remaining forces and moments have lesser influence on steering effort with the exception of longitudinal force, Fx, which can contribute significantly to steering effort under braking.

The lateral force acting through the design trail length produces a moment about the steering axis. The lateral forces produced by the tires while driving in a straight-line are relatively small compared to those during cornering. In a straight-line, they are basically required to counteract the moment produced by the different tractive forces from the rear tires. The aligning moments however are considerably larger during straight-line driving versus cornering. Figure 2 shows this relationship.

In general, aligning moment is the primary contributor to steering effort during both straight-line driving and cornering. During cornering, lateral force acting about the steering axis through the trail length is a secondary contributor given relatively short design trail length.

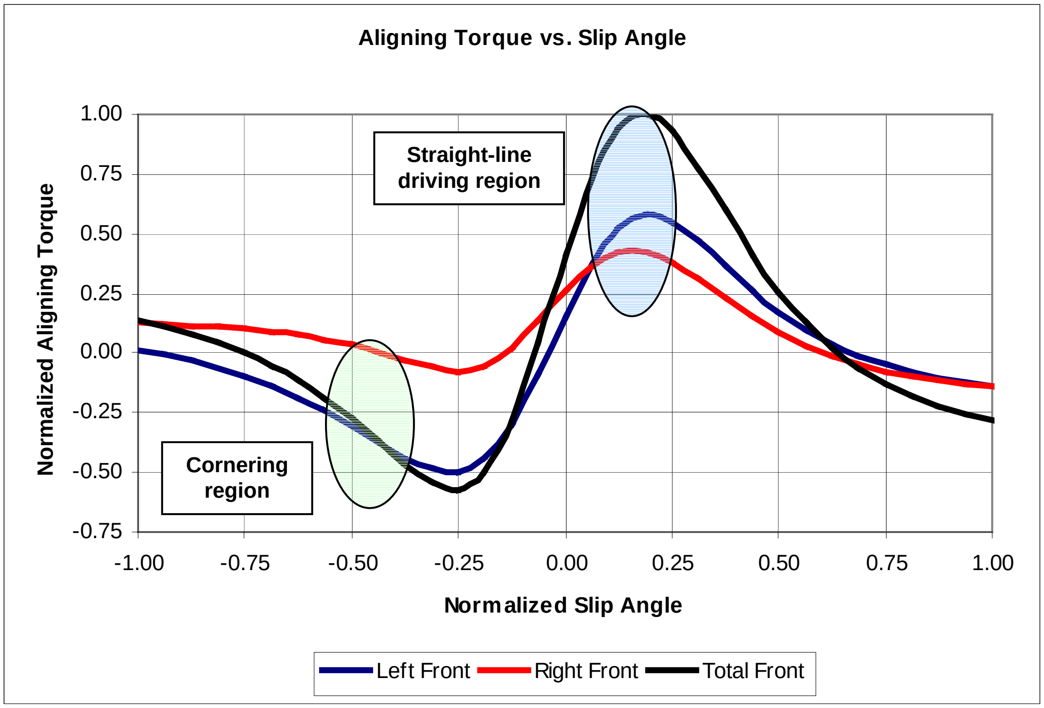

Figure 2: Aligning Torque vs. Slip Angle

Simulations and Results

Newman Haas Racing utilizes ADAMS/RaceCar for its simulation-based racecar development programs. The simulations used in development of this paper were steady-state events including Constant Radius and Straight Line Drive. Post-processing was performed using a combination of ADAMS/PPT, Matlab, and Microsoft Excel.

ADAMS simulations were run to evaluate steering effort during straight-line and cornering conditions. Setup changes were made to evaluate their effect on steering effort. These changes include rear tire stagger, design trail, front camber, and caster. Figure 3 shows steering effort values for both straight-line and cornering conditions. Figure 4 shows the change in steering effort magnitude relative to the baseline setup.

As shown in Figure 1, the asymmetric setup shifts the zero steering torque crossing to a relatively high, non-zero lateral acceleration value. This characteristic can be disconcerting to a driver. As the driver rotates the steering wheel to turn into the corner, the steering wheel torque is decreasing. At some point, the steering wheel torque is

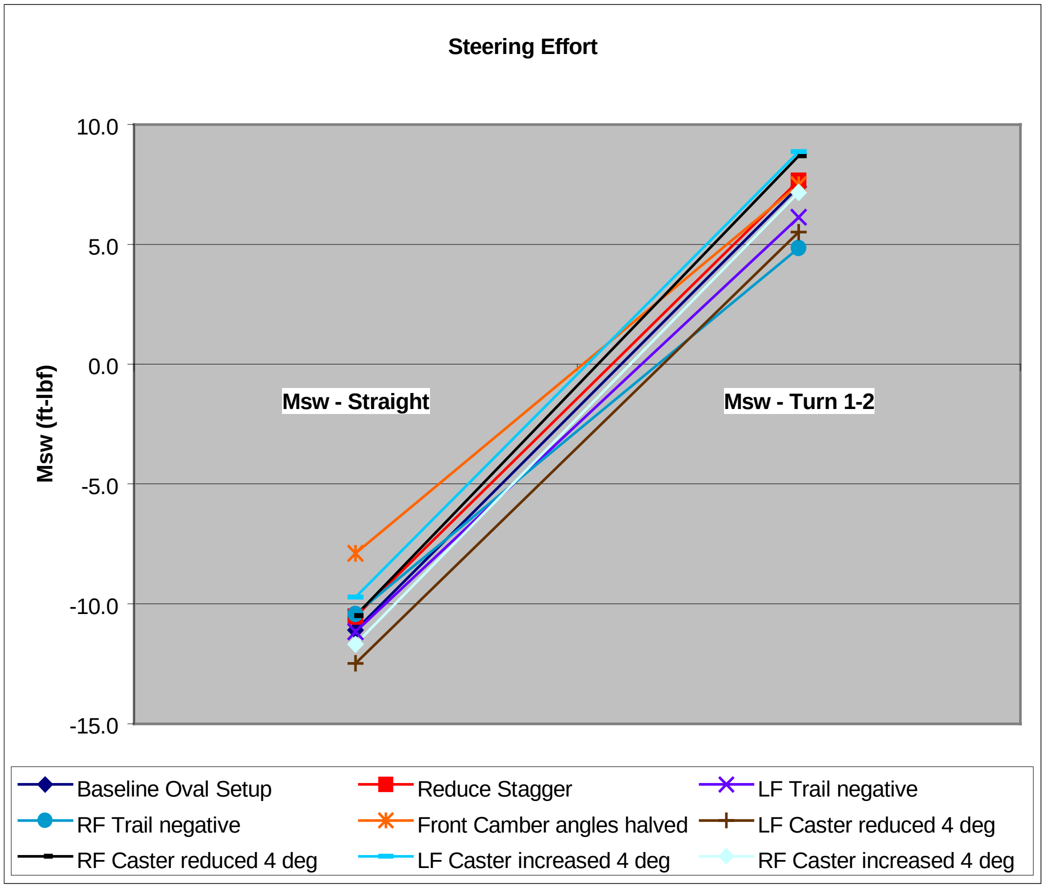

Figure 3: Steering Effort

zero while the vehicle is producing a lateral acceleration. The steering at this point feels very light and gives a disconnected feeling to the driver. As the driver continues rotation of the steering wheel, the steering effort increases with increasing lateral acceleration. The hypothesis is that by reducing the lateral acceleration at which zero steering torque occurs the driver's feeling of stability will be improved. The result would be increased confidence in the ability to control the car's response giving more consistent or potentially reduced laptimes. Figure 5 shows both peak steering effort values and lateral acceleration values at zero steering effort for the setup changes. In the discussions below, zero steering effort crossing refers to lateral acceleration values at zero steering effort.

Rear Tire Stagger

As discussed in the Steering Effort Mechanism section, the lateral forces produced by the tires while driving in a straight-line are basically required to counteract the moment produced by the different tractive forces from the rear tires. Therefore, reducing the tractive force difference between the rear tires will decrease the moment produced and reduce the front lateral force and steering effort required to counteract this moment. One method of reducing the tractive force difference is by reducing stagger. Stagger is defined as the difference between right rear and left rear tire diameter. Reducing rear tire stagger resulted in relatively small steering effort changes due to the secondary contribution of lateral force on steering effort. A 0.1g reduction in zero steering effort crossing is shown in Figure 5. Rear tire stagger plays an important role in racecar handling, setup style, and tire wear. Therefore, it is unlikely that stagger would be changed primarily to affect steering effort.

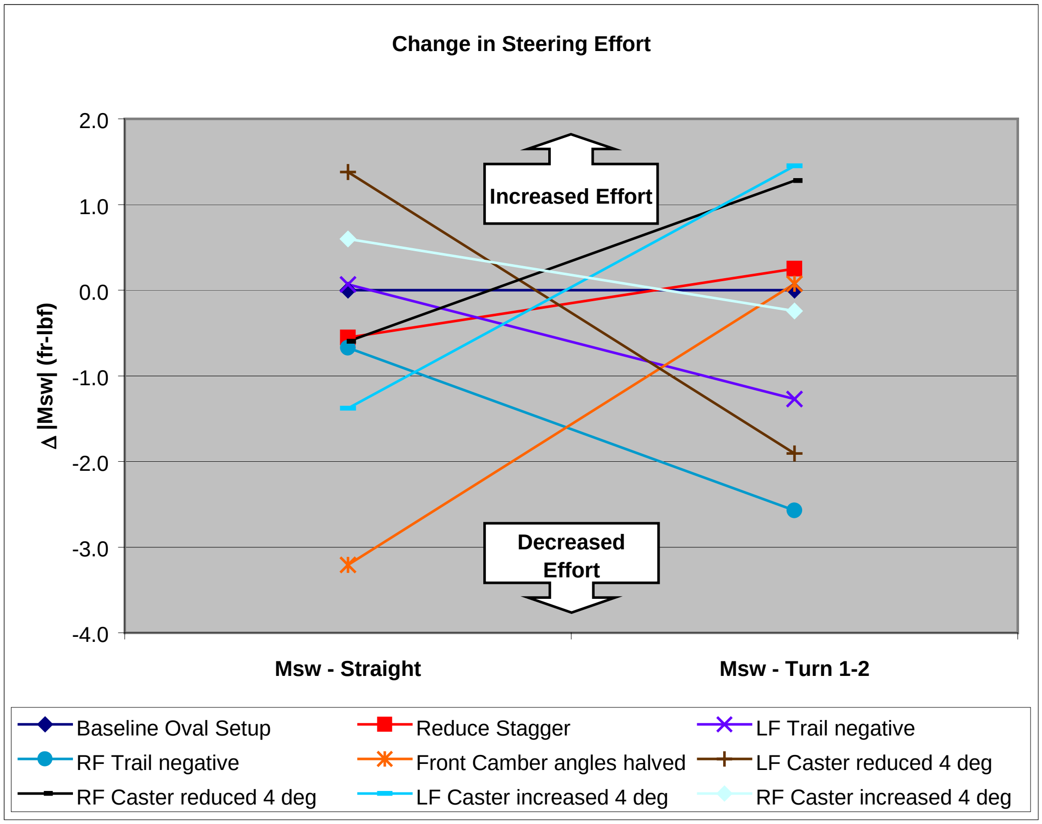

Figure 4: Change in Steering Effort

Design Trail

With relatively small design trail dimensions, the lateral force has a secondary effect on steering effort compared with aligning torque. However, during cornering the large lateral forces can be used to produce moments about the kingpin axis for reducing steering effort. In the extreme case, negative design trail can be used to produce a moment opposing the aligning moment. In this paper, positive trail is defined as the kingpin axis intersecting the ground forward of the of tire contact patch center. The Baseline Oval Setup included positive design trail for both front wheels.

The results of negative design trail dimensions shown in Figure 4 are considerable reductions in cornering steering effort when lateral forces are large and small changes in straight-line steering effort when lateral forces are minimal. A drawback to negative design trail is difficulty for the driver in maintaining a desired trajectory, or "wandering," particularly on rough road surfaces.

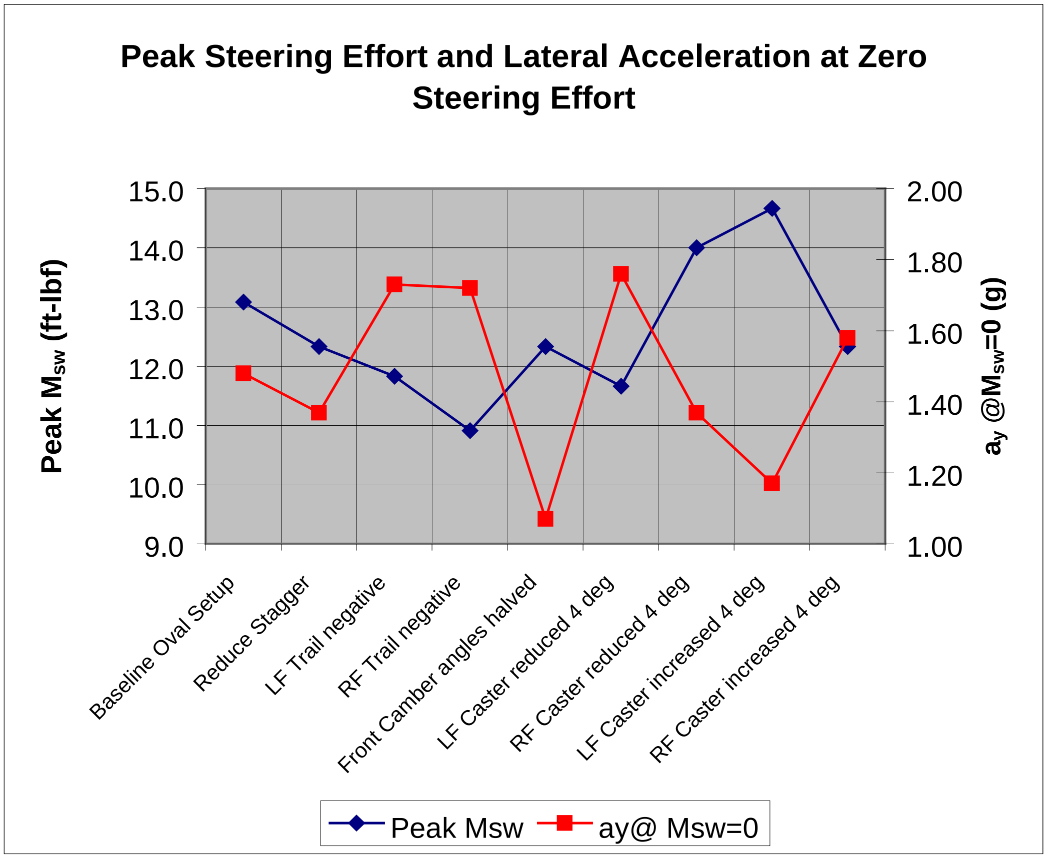

Figure 5: Peak Steering Effort and Lateral Acceleration at Zero Steering Effort

Camber Angle

Aligning moment is sensitive to camber angle particularly at small slip angles, i.e. while driving in a straight-line. Halving the front camber angles resulted in reducing straight-line steering effort by 30%. The drawback to reducing camber is the reduction in peak lateral force capability.

Caster Angle

Each of the caster angle changes resulted in comprises of decreasing straight-line steering effort while increasing cornering steering effort or vice-versa. This is due to the multiple changes that occur when caster angle is changed. These include changing the inclination angle of the steering axis, the camber gain versus steering angle relationship, and the load transfer distribution due to tire force and moment changes at the altered camber angle. These multiple changes necessitate an evaluation of their individual effects on the handling and cornering capability of the racecar. Therefore caster angle changes can result in steering effort improvements, but typically simultaneous changes are made in static alignment and setup variables.

Conclusions

Evaluating the setup changes using Figure 4 portrays the norm in racing that most changes involve trade-offs. The majority of setup changes reduce either straight-line or cornering steering effort, but generally not both. One exception is the reduction in RF Trail that reduces steering effort in both conditions. The trade-off for this change can be “wandering” on uneven track surfaces. The largest magnitude change was achieved by halving the front camber angles, which reduced straight-line steering effort by 30%. Unfortunately, halving the camber angles is not desirable due to the resulting loss of grip during cornering. A combination of these changes may yield a steering effort reduction in both conditions, but other potential disadvantages must be carefully weighed.

Analyzing the potential improvements in Figure 5 leads to the same conclusion as found in Figure 4 that trade-offs are generally required with any change. As discussed above, a reduction in RF Trail reduced steering effort in both straight-line and cornering conditions. In addition to potential “wandering” problems, Figure 5 shows that the zero steering torque crossing is increased by 0.2g. Halving the front camber angles yielded the largest magnitude reductions in straight-line steering effort and zero steering torque crossing, however as noted above this is not a desirable change due to loss of cornering grip. Increasing LF Caster produced a compromise in terms of steering effort by decreasing straight-line effort but increasing cornering effort by the same amount. However, the zero steering effort crossing was reduced by 0.3g. Implementing this change requires evaluation of other effects including camber change and crossweight.

In summary, the advantages and disadvantages of potential changes must be weighed, and ADAMS gives us the ability to quickly evaluate individual or combinations of changes. Both transient and steady-state simulations are ultimately used in this process. The combined changes that yield net improvements in steering feel and laptime cannot be discussed in this paper due to the competitive nature of Champ Car racing, but without ADAMS the investigation and evaluation of these changes would not be nearly as efficient. In addition to setup changes, ADAMS allows the investigation of design changes intended to improve and optimize the balance of the factors being weighed. This can be a substantial cost savings versus designing and manufacturing parts for on-track testing.