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Design of an Electronic Differential for a Formula Electric Racecar

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Racecar performance, even on a collegiate or student level, depends on a multitude of factors, some of which are incidental to the track the race will be run upon. A careful balance of power, speed, and control needs to be maintained in order to optimize a vehicle's performance on the racetrack. As UC Irvine's entry into the 2012 Energy Invitational race, Gamma has been a testbed for different drive technologies at some point in time, and is now being used to investigate the effects of active torque bias on vehicle handling under racing conditions.

INTRODUCTION

A vehicle turning a corner experiences a number of forces that can affect its handling adversely. Slippage of the tires induced by the relative motion of the inside to outside tyres, as well as the forced slowing of the inside tyre due to drag both contribute to wear on the tyres and can cause loss of traction, or catastrophic failure of the tyre. The mechanical differential that has to cope with these forces has undergone a number of iterations, ranging from locked axles to open differentials, each with their respective advantages and disadvantages, which has spurred on the development of the limited-slip differential that is more commonly used today.

The emergence of electric motors and their use within vehicles has necessitated a shift from purely mechanical differentials to take into account the different behavior of electric motors and the differing power trains. Electric motors which, unlike their internal combustion engine counterparts, develop maximum torque at zero rpm, are more commonly used to provide individual power to a wheel due to their weight and size, unlike the traditional central drive shaft in use in internal combustion engine vehicles. This allows for much more flexibility in how the power-to-wheel is transmitted and adjusted depending on the driving conditions. With an electric vehicle, four- or even just two-wheel drive is capable of independently controlling motor output from the shaft to the wheel [1], contributing to stability, steering assist, and improving handling. Mechanical differentials designed to split and optimize power from one drive shaft can be replaced or supplemented by electronic differentials, which actively adjust the power to each driven wheel depending on the driver input as well as a variety of road conditions to provide maximum torque and traction under a wider range of conditions that would otherwise force a compromise in performance in traditional mechanical differentials.

The vehicle that has been nicknamed Gamma is the testbed for a number of future vehicle technologies, ranging from drivetrain and powertrain improvements designed to compete

at the FSAE Electric events to the UC Irvine-hosted annual Energy Invitational, which prioritizes fuel economy and



Fig. 1. Gamma rear-wheel drive setup. Dual PMG-132 and independent rear axle control.

vehicle performance. As UC Irvine's 2012 entry into the Energy Invitational as an all-electric racecar, the vehicle encountered a number of shortcomings due to its mechanical design; having originally been a gasoline-electric hybrid. To counter these shortcomings and improve the performance of future vehicles, a number of changes have been made and tested on the vehicle.

As a heavy, wide car, steering and handling is a prominent issue, and quite crucial for performance on a track where energy consumption, recovery, and cornering speed are key, all of which are in demand at the Energy Invitational and are a concern for the majority of electric vehicles in commercial and military use. Besselink [2] has proposed a system wherein steering and traction are integrated utilizing the differential driving torque of the rear axle to assist steering; furthermore, Jang et al. [3] and Nozaki [4] have suggested the use of differential braking to correct steering maneuvers. Wang et al. [1] builds on those to present a computerized torque control for 4WD vehicles to supplement or replace power steering.

Tabbache et al. [5] present a look from an alternative perspective, by improving vehicle stability on a two-motor, front wheel-drive vehicle for commercial use to simplify and improve reliability of vehicle components. However, while important topics in and of themselves, this paper will approach the issue from a racing approach, something touched on by Nozaki. With a 66-inch track and an 80-inch wheel base, set two inches above the road surface at static displacement, Gamma is stable enough for high-speed cornering maneuvers, but lacks the control and handling to take curves at more than a token speed.

The vehicle, shown in Fig. 1, has been tested and upgraded in its various forms since the summer of 2012, and is currently being powered by a pack of 70Ah LiFePo4 batteries and twin, 72V, 7.2kW Perm GmbH PMG-132 electric motors on its rear half-shafts. The objective of this paper is to investigate the effects of active, steering-induced differential torque vectoring on the vehicle's performance under actual racing conditions, and evaluate the benefits and shortcomings of such a system for use in high-performance situations such as racing, something explored in a similar manner theoretically by Merkt and Gilbert [6].

ELECTRONIC DIFFERENTIAL AND POWERTRAIN

As the very basis for testing, Gamma has been retrofitted with a simple analog closed feedback control system that directly ties into the throttle potentiometer, shown in Fig. 2. A pair of potentiometers directly attached to the steering linkage determine steering angle, and directly feed into the motor controllers' throttle input. The electronic differential is designed to go onto the car in two phases; a static, pre-determined setting that will cause predictable and comparable behavior on a static cornering test at constant velocity, and a second, dynamic phase tied into the vehicle's steering input which will test the variation from the static setting in terms of handling, control, and speed.

The entire control system is completely analog for simplicity and reliability, and consists of a parallel setup of three resistive components, the throttle potentiometer (directly attached to the driver's accelerator pedal), the steering input potentiometer, and a static steering offset resistor that is used to change the range of the torque bias between the wheels for different testing setups, and can later be exchanged for a third dynamic component that can actively alter the torque bias envelope depending on the driving situation.

Determining the effect of this adjustment to the throttle input of each motor as well as the optimal level of adjustment depending on the driving situation will then yield a setup that than be further developed for advanced control and stability behavior under a multitude of high-performance conditions. The overall effect has been estimated by assessing the weight transfer as a function of vehicle turn radius to the rear wheels, as well as throttle bias between the inside and outside wheels.

Gamma's power source is a pack of 22 CALB LiFePo4 batteries, outfitted with the CleanPower MiniBMS system and connected to two Alltrax AXE7245 controllers. The PMG-132 motors are geared at a ratio of 1:3.5, and the throttle potentiometers are set up to allow for individual throttle control.

Currently, testing has been conducted with the vehicle to establish a baseline performance, called Phase 1 herein, and with the static torque bias, called Phase 2. The dynamic, steering-induced torque vectoring system (Phase 3) is currently mounted on the vehicle and being tested.

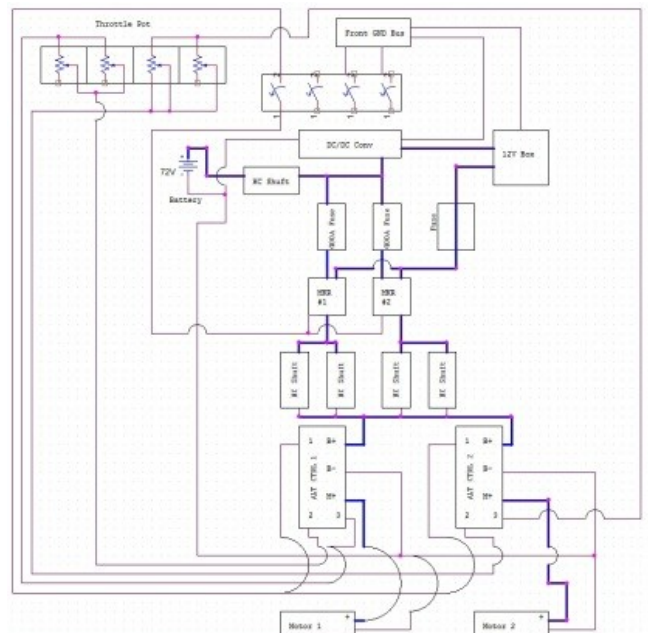


Fig. 2. Phase 2 analog control setup, including an independent throttle potentiometer and static torque bias potentiometer for each motor.

VEHICLE OPERATION UNDER PRE-RACE TESTING CONDITIONS

Testing was conducted in three phases, in order to facilitate comparison and to establish a testing and development procedure for following years.

Phase 1 is the base vehicle, with no electronic differential, with both rear motors driven off a single throttle signal. This configuration was tested extensively to train drivers and establish a baseline for comparison. SAE-standard 50-ft inner diameter skid pad runs and 144-ft acceleration runs were timed and used as the basis for determining the car's handling.

Phase 2 has just concluded at the time of writing of this article, and has seen the testing of a number of static torque bias settings on the same 50-ft diameter skid-pad as the baseline for comparison. Driver training became essential at this stage in order to produce reliable and consistent data in order to be able to proceed to Phase 3, which is the dynamic torque vectoring.

Testing procedures for all phases consist of a series of six timed laps around the skid pad, with the initial two laps devoted to the driver accelerating the vehicle to a comfortable limit, and the latter four reserved for pushing the vehicle to the maximum attainable speed. The times are averaged to account for human error and inaccuracies, and have a cumulative standard deviation of 0.2 seconds thus far.

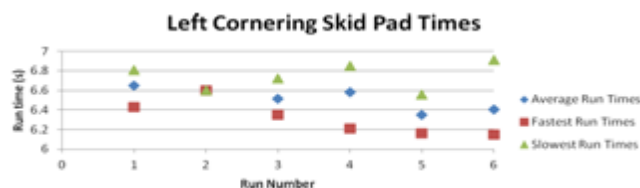


Fig.3. Left cornering times.

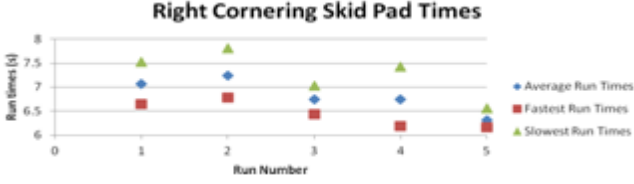


Fig. 4. Right cornering times.

A. Phase 1 Baseline Testing Results

The telemetry on Gamma includes real-time and logged RPM, current, voltage, and power usage data; the initial Phase 1 baseline testing was conducted as much to collect data as to establish the validity of the drivetrain and power systems, as well as determine the power consumption of the vehicle under operating conditions, as energy efficiency is one of the concerns at the Energy Invitational race event. The baseline vehicle was tested from September to November of 2012 on an SAE-standard 50-foot (15.25 meter) diameter skid pad, comprising both left- and right-handed turns.

For testing purposes, the drivers were instructed to continue accelerating until the vehicle started to lose traction in the rear, causing it to begin sliding out of control, and the ease off the throttle until a maximum speed at which the vehicle could reliably orbit could be found. For the majority of Phase 1 testing, due to the damage to the car's primary LiFePo4 battery pack caused by previous years' wear, Gamma was operated on a pack of six lead-acid, 35Ah car batteries capable of providing short-term continuous power to the vehicle.

Figs. 3 and 4 show the resulting right and left cornering skid pad times, respectively. The time evolution of the run times show that the driver is getting more comfortable with the vehicle, at which point it was deemed possible to proceed to the next phase of testing.

In addition to driver training and basic skid-pad data, Phase 1 was also used to run a series of acceleration tests to assess the individual and combined motor acceleration of the car, as well as gather power consumption data for skid-pad and acceleration driving behavior. Fig. 5 shows the results of the acceleration tests in Gs pulled.

This testing allows for the calculation of an averaged optimal vehicle speed, v_t , of 8m/s for orbiting the 50-ft diameter skid-pad.

B. Phase 2 Static Torque Bias Results

Phase 2 is the implementation of a static torque bias for a given turn radius and speed to investigate the effects of reducing the inside wheel torque to compensate for the reduced traction limit of the rear inside wheel. Fig. 6 shows a free-body diagram of the vehicle in a generalized turn. The vehicle currently has a weight distribution of 30/70, that is, the centre of mass is located 70% of the length of the car towards the rear. As such, the left and right sides each take a load of 215kgs statically.

Given a track of 66 inches and the wheel base, one can calculate the torque limits on the wheels both for acceleration

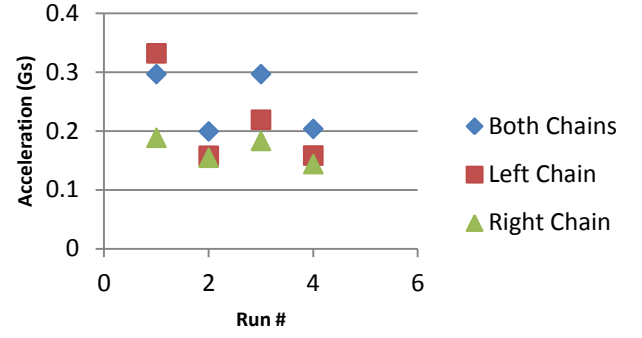


Fig. 5. Acceleration test results for individual and combined motor torques.

as well as for cornering (eqns. 1 and 2) by taking the moments around the tyres and comparing that to the torque applied by the motors [7].

$$m_{total} \cdot h_{cg} \cdot g = (F_{front} \cdot l_{front} + F_{rear} \cdot l_{rear}) \quad (1)$$

$$m_{rear} \cdot g \cdot r_{tyre} = T_{rear,limit} \quad (2)$$

Where h_{cg} is the height of the centre of mass from the ground, F_{front} and F_{rear} are the weights on the front and rear tyre pairs of the car, respectively, l_{front} and l_{rear} are the distances from the centre of mass to the wheels, and $T_{rear,limit}$ is the torque limit on the rear tyres for cornering. During pure acceleration, the weight of the car shifts backwards; similarly, as the vehicle turns a corner, the centripetal acceleration causes a load shift from the inside to the outside tyres as the car travels along a tangential direction, causing a reduced traction limit on the inside rear (driven) tyre that, if surpassed, can cause the vehicle to oversteer and lose control.

Based on Phase 1 results, the centripetal acceleration, a_c in Fig. 6, acting on the car can be calculated, resulting in an average of 0.85Gs for the 50-ft diameter turn. From there, the shift of the inside-to-outside load can be calculated, adjusted by that sideways force, resulting in a loss of 0.34Gs of load on the inside tyre, and a corresponding increase in load on the outside. For Gamma, this means a reduction in traction limit from 974.5Nm of torque on the rear inside tyre to 643Nm, a reduction of 34%.

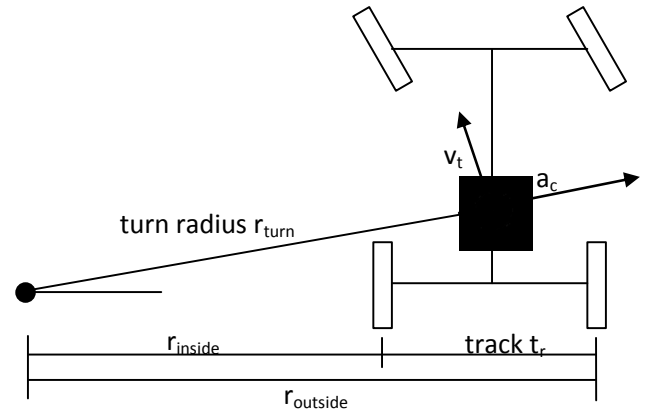


Fig. 6. Vehicle free-body diagram in a left-hand corner.

The PMG-132 motors at maximum current can put out a combined torque of 2784Nm from both motors, far surpassing the traction limit of both rear tyres for such a turn.

Phase 2 testing was conducted with this in mind, and two torque bias settings were tested for a left-hand turn in order to compare performance and driver response with the baseline. Due to driver input, a parallel analog system was chosen in order to decrease throttle sensitivity at the low and increase sensitivity at high throttle settings, resulting in a low differential torque between the tyres at low speeds, and higher differential torque at high speeds.

Fig. 7 shows the differential throttle inputs for the inside-to-outside tyre setting for various torque bias potentiometer settings. As can be seen, not only does the bias potentiometer directly affect the throttle signal passed to the inside motor, but it also scales with the actual throttle pedal input. Three settings were chosen to be tested according to the Phase 1 results in order to compensate for a 34% loss in traction limit on the inside tyre: a bias setting of 50%, a bias setting of 30% and a bias setting of 100%.

The former was selected in order to closely match the reduced torque capability of the inside tyre, while the latter two were chosen for a more extreme example, to determine if further reduction of applied throttle to the inside would yield favorable results when compared to the potential loss of applied power to the wheels.

Fig. 8 shows the results of Phase 2 testing, with a new baseline added due to the switch to a new LiFePo4 battery pack. The old Phase 1 baseline is shown for comparison.

The new baseline times using the Phase 2 setup - which was otherwise identical to the Phase 1 baseline testing with the exception of a new LiFePo4 battery pack - were considerably faster, a change attributed to both driver familiarity with the vehicle and the new battery pack, as times on average were consistent. Similarly, the Phase 2 test times with the 50% bias, matching roughly a 30% reduction in inside wheel torque, were on par with the baseline times for Phase 2, which is encouraging, as drivers have indicated that the new driving behavior is causing less oversteer and a more pronounced understeer, giving them time to correct.

However, Phase 2 times for a 100% bias setting, i.e. zero power to the inside wheel, were considerably slower than the baseline times, roughly on par with the Phase 1 baseline times, attributed to the lack of power to the wheels as well as the uncontrollability of the car. Data for the 30% bias could not be taken, as no driver could reliably complete a test set without spinning out the vehicle due to driving instabilities.

C. Phase 3 Dynamic Torque Bias

Based on the Phase 2 data, Phase 3 is being put into effect currently, directly linking a steering input potentiometer into the analog control system to actively change the torque bias as a function of steering input, as shown in Fig. 9. At zero steering angle, the system applies full throttle to both motors, and decreases the throttle to the inside motor as per Fig. 9 depending on steering angle α .

The initial Phase 3 setup consists of the original 10k Ω throttle potentiometer tied into the accelerator pedal, but in its

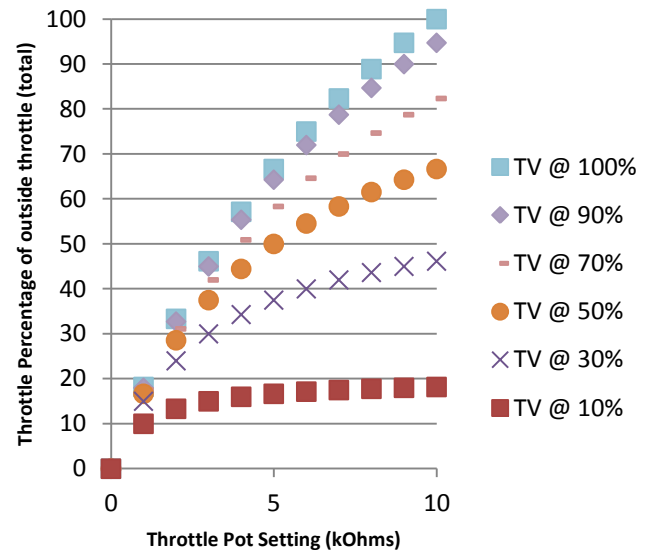


Fig. 7. Differential torque (throttle) for various bias potentiometer settings for Phase 2 testing. Torque vectoring settings of 50% and 30% were selected for testing during Phase 2.

first iteration features a 5k Ω steering offset resistor in series with a 5k Ω steering input potentiometer to replace the static offset potentiometer of Phase 2. This set of resistors were chosen based on the Phase 2 data, in order to provide a torque vectoring envelope ranging from maximum throttle on a straightaway to a 33.3% reduction in inside wheel torque for maximum α , with an increasing torque differential for increasing throttle settings.

Merkt [6] calculates the speed difference between inside and outside tyres as follows, in eqn. 3.

$$\Delta v_{i-o} = \sqrt{\frac{a_c}{r}} \cdot t_r \quad (3)$$

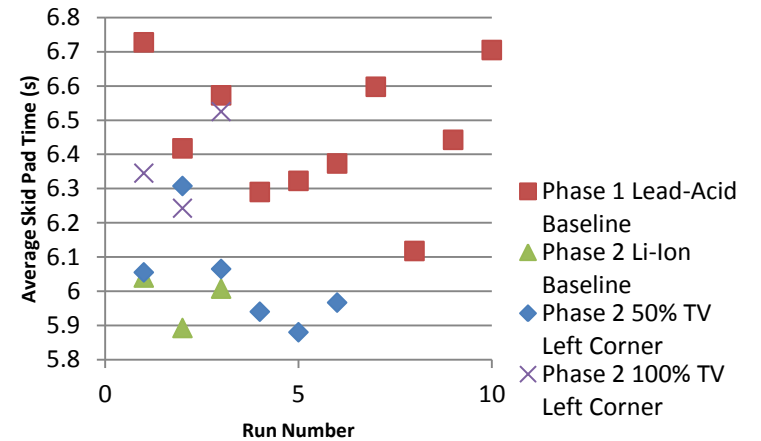


Fig. 8. Comparison of average times for Phase 1 baseline with lead-acid battery pack, Phase 2 baseline with LiFePo4 battery pack, and Phase 2 results with 100% and 50% torque bias settings. Note that the Phase 2 baseline is considerably faster than the Phase 1, attributed to the change in batteries. Similarly, Phase 2 times with 50% bias were on par with the baseline, while the times with 100% bias were considerably slower due to the loss in power.

where t_r is the track of the car, and Δv_{i-o} is the difference of the inside to the outside wheel speeds. This can then be used to further tune the actual steering input bias and offset to allow the car to match a variety of steering conditions.

Under current driving conditions, for a 50-ft diameter skid-pad, eqn. 3 yields a speed difference of 0.88 m/s between the inside and outside tyres, or, fractionally, in eqn. 4:

$$\frac{v_{inside}}{v_{outside}} = \frac{r-0.5t_r}{r+0.5t_r} \quad (3)$$

as a function of the track t_r of the car and the turn radius r . Assuming a car capable of maintaining a 0.85G turn with a given track of 66 inches, this would simplify to:

$$\frac{v_{inside}}{v_{outside}} = \frac{(r-0.84m)^2}{r^2-0.176m^2} \quad (4)$$

which can then be used to set the steering and throttle limits for the bias settings as a function of the maximum steering angle as a second criteria for throttle biasing, in addition to the torque limiting.

CONCLUSIONS

Fig. 8 demonstrates that it is possible to operate the car at reduced inside wheel power and maintain good cornering behaviour; however, according to feedback from the drivers, too much torque bias in actuality destabilizes the vehicle during high-speed turns, causing spin-outs and loss of control as well as resulting in a loss of cornering speed due to reduced wheel speed. A few drivers have attempted to compensate for this sudden loss of traction by drifting the vehicle around the circuit, with limited success. However, an incremental and limited reduction to inside wheel torque matching with the reduced ability of the inside rear tyre to take lateral loads, can potentially be beneficial and will be further investigated during Phase 3 testing.

It is also hoped that by making the torque bias dynamic, as opposed to the static bias of Phase 2, driver correction of over- or understeer conditions will see a much improved effect and allow for more effective driving on the racetrack and during testing. Initial results from the first stage Phase 3 testing will then lead to further advancements of the system if it proves utilizable and eventually result in a port to a fully digital control system capable of adjusting to the track and driver input to allow for optimal high-speed cornering.

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