Optimization of the centre of mass position of a racing motorcycle in dry and wet track by means of the “Optimal Maneuver Method”

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3 authors:

Vittore Cossalter
University of Padova

Roberto Lot
University of Southampton

Davide Tavernini
University of Surrey

Optimization of the centre of mass position of a racing motorcycle in dry and wet track by means of the "Optimal Maneuver Method"

Vittore Cossalter, Roberto Lot, Davide Tavernini
Department of Industrial Engineering (DII), University of Padova
Via Venezia, 1 – 35131 Padova - Italy
vittore.cossalter@unipd.it
roberto.lot@unipd.it
davide.tavernini@studenti.unipd.it

***Abstract*- The "Optimal Maneuver Method" is an application of the optimal control theory that basically simulates an ideal driver and computes the actions and the trajectory to complete a maneuver in the minimum time.**
As an application of this method a 125 cc motorcycle and a real race circuit, in both dry and wet conditions, have been simulated, and the validation of the results by means of a comparison with real telemetry data is discussed.
Afterwards two significant quantities, the height and the longitudinal position of the centre of mass of the vehicle, have been considered. The influence of variation on the minimum lap time, in the two track conditions discussed above, is presented.

I. INTRODUCTION

Real riders' performance is influenced by their experience and riding skills. On the contrary an 'ideal rider' [1] is able to ride a vehicle at its maximum potential, every time adapting riding style to different vehicles and different scenarios (dry and wet conditions, geometry of the path, etc.).

In a recent study Kelly and Sharp [2] support the approach of replacing the driver of a race car with inputs calculated solving an optimal control problem.

The purpose of this research is to perform an optimization based on the concept of maneuverability, i.e. the ability of a vehicle to complete a given maneuver as fast as possible without exceeding existing physical limitations, like tire adherence or road borders, but without considering the physical and mental pilot effort, that are concepts typical of handling. According to this, the choice of an ideal optimal rider is required.

In this work the "Optimal Maneuver Method" is proposed as an advanced tool that can help engineers to optimize some relevant parameters of the vehicle geometry, without building prototypes, e.g. the optimization of the gearbox of a racing motorcycle proposed by Cossalter et al. [3].

This research deals with two important parameters for the behavior of a motorcycle: the height h and the longitudinal position b of the centre of mass (CoM).

A study by Sakamoto et al. [4] has shown the existence of an optimal position of the centre of mass, in order to reach the minimum maneuver time. It can vary with the properties of the analyzed course (i.e. corner radius, corner distance and straight length), because of the different acceleration limitations that occurs in a specific maneuver.

The importance of these two quantities h and b is essentially correlated to the concept of load transfer from the rear wheel to the front one during braking, and from the front to the rear one during acceleration and to the concept of static loads.

A higher CoM allows more load transfer to the rear wheel with an increased traction at the exit of a turn, but it can also cause wheelings (i.e. lifting of the front wheel) at lower longitudinal accelerations with respect to the standard position and the same for braking and stoppies (i.e. lifting of the rear wheel). Same considerations are also valid for the longitudinal position of the CoM which influences the vertical loads on both the wheels.

The advantages or disadvantages of the choice of a particular position of the centre of mass depend mainly on track geometry, engine power and the tires adherence due to wet or dry ground conditions. These can change many times during the race week end.

This is the reason why it is very important for a racing team to have a starting point, optimized on the current conditions of the road, to submit to the rider during several round of testing.

II. THE OPTIMAL MANEUVER METHOD

In this section a brief description of the "Optimal Maneuver Method" is reported in order to explain the basic principles and the underlying mathematical model.

A. *Basic Principles*

Let's consider a racing driver who has to run on a given circuit by a given vehicle. He has to find the best trajectory, among many possible ones, and speed profile. The "Optimal Maneuver Method", introduced first by DaLio et al. [5, 6], works as a virtual best driver, i.e. it finds the best trajectory and the driver's actions (such as steering torque, throttle, braking, etc.) that moves the assigned motorcycle along the given circuit performing the minimum-lap-time where the physical constraints (tire adherence, propulsive power, etc.)

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and the environmental constraints (road boundaries, etc.) are fully satisfied.

Considering the optimal control theory point of view, the simulation of a motorcycle minimum-lap-time problem is posed as the constrained minimization of an integral target function.

The constraints include: the equations of motion of the rider-motorcycle system given by:

$$A(x(s),p(s))x'(s)-f(x(s),u(s),p(s))=0 \qquad (1)$$

where:

s = curvilinear coordinate, i.e. the position along the track
u = rider controls
x = mechanical system state vector
p = parameters of the model

the initial and the final conditions, i.e. vehicle velocities and positions on the track at the start and finish line given by:

$$b_i(x(0),p(0))=0 \qquad (2)$$

$$b_f(x(L),p(L))=0$$

Regarding the considered problem, in which a closed circuit is studied, some cyclic boundary conditions have been introduced on vehicle longitudinal velocity, lateral position on the track and longitudinal thrust force. These allow to impose the same free value for a specific variable both at the initial and at the final point.
Furthermore, the constraints include some inequalities:

$$g(x(s),u(s),p(s))\leq 0 \qquad (3)$$

these consist of the motorcycle physical limitations (e.g. maximum engine torque, etc.) the track geometry, and the tire-road friction.
The inequalities are then replaced with some penalty functions basically expressed by:

$$p_\varepsilon(x)=-\varepsilon\log\cos\left(\frac{\pi}{2}\frac{x}{F_y^{\max}}\right) \qquad (4)$$

In conclusion the target function results expressed as follows:

$$\int_0^L\frac{1}{V}ds+\int_0^L\sum_k p_\varepsilon\left[g_k\left(x(s),u(s),p(s)\right)\right]ds \qquad (5)$$

where L is the path length.
The first integral is the minimum time cost in which V is the velocity along the path.

The result of the optimal control problem completely describes both the dynamics of the motorcycle-rider system during the minimum-lap-time maneuver and the rider inputs that produce the maneuver [7, 5]. One of the main advantages of this method is that no 'driving rule' has to be predefined; they emerge from the optimality criterion and from the solution of the control problem itself.

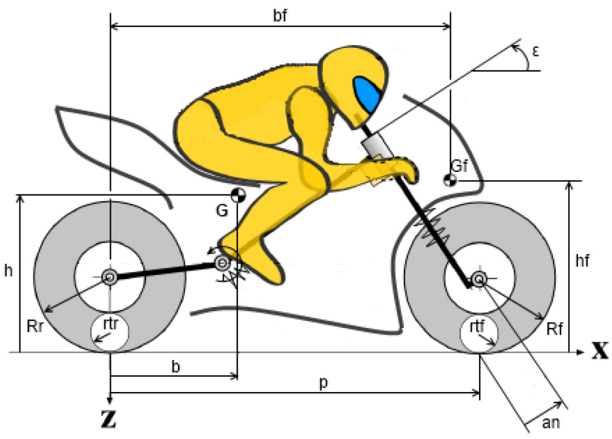

Fig. 1. Motorcycle 9 degrees of freedom model main parameters.

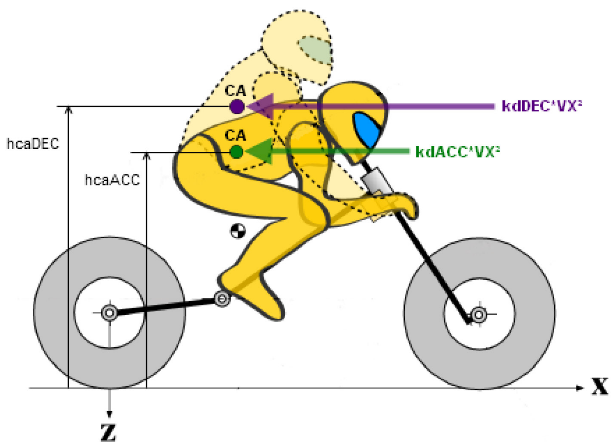

Fig. 2. Aerodynamics parameters variation due the longitudinal acceleration: kdDEC and hcaDEC for braking conditions and kdACC and hcaACC for acceleration condition.

B. *Motorcycle Model*

The motorcycle is represented in Fig.1 and includes six rigid bodies: the front and the rear frames, the front and the rear unsprung masses, the front and the rear wheels. Regarding the front frame, it includes the front suspended mass, i.e. the handlebar including different accessories connected to it, the triple clamps and the fork sprung parts. The rear frame is composed of the chassis, the engine, the tank and the rider body.
Both the wheels are considered as pure moments of inertia about their spin axes, whereas their masses (tires, brake discs, etc.) are included in the unsprung masses.
The front unsprung mass includes the unsprung part of the

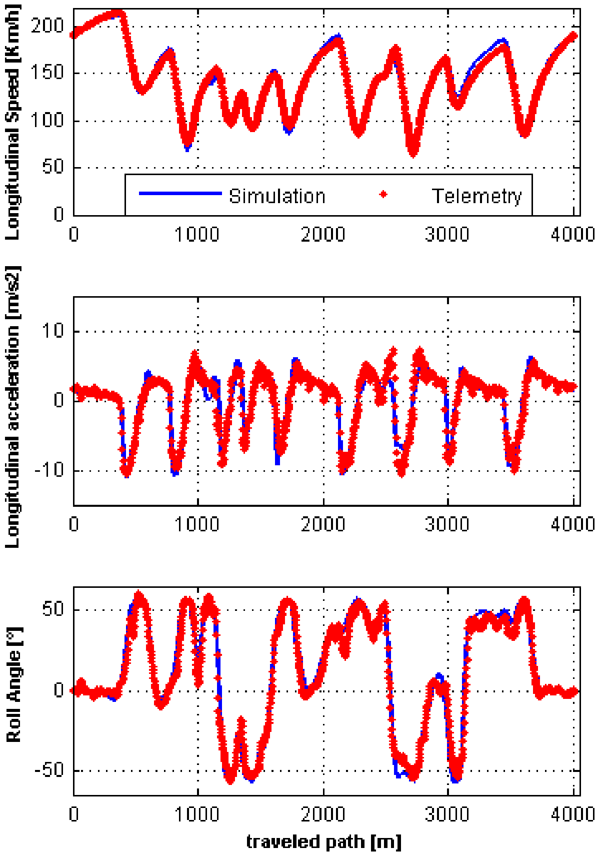

Fig. 3. Comparison between simulations (Optimal Maneuver Method) and telemetry data. Longitudinal speed, Longitudinal Acceleration, Roll angle, in DRY conditions.

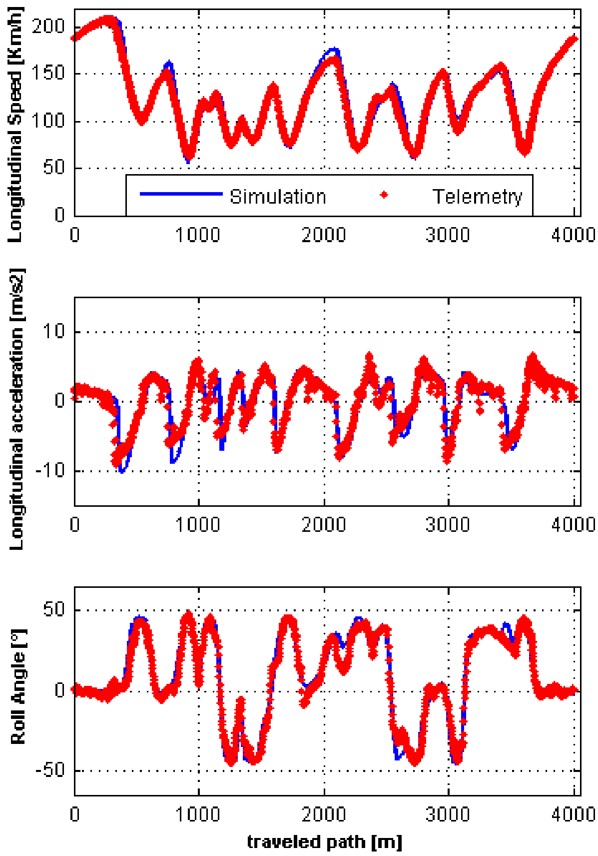

Fig. 5. Comparison between simulations (Optimal Maneuver Method) and telemetry data. Longitudinal speed, Longitudinal Acceleration, Roll angle, in WET conditions.

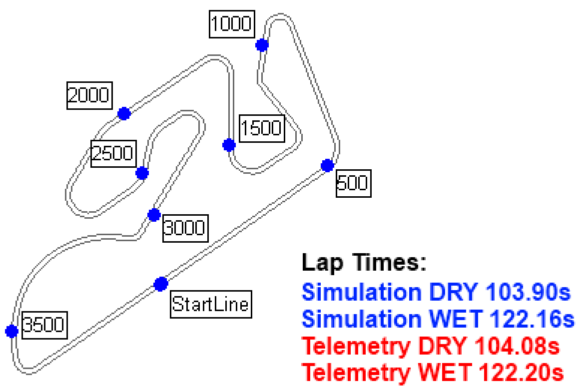

Fig. 4. Valencia circuit track and lap times performed by Optimal Maneuver Method and real rider.

forks and the front brake caliper, whereas the rear unsprung mass includes the swingarm and the rear brake caliper. The rear suspension is described as a non-linear torsion spring-damper system, whereas the front one as a non-linear traditional one. Suspension kinematics, elastic and damping properties are also included.

Ultimately, the motorcycle model has nine degrees of freedom: forward speed, lateral speed, yaw angle, roll angle, pitch angle, steering angle, centre-of-mass vertical movement, front and rear suspension travels.

Tires are modeled with a toroidal cross-section and generate three forces (i.e. longitudinal, lateral and normal forces) at the actual contact point. In particular, the lateral forces are expressed with a simplified version of the Pacejka formula as a function of the side-slip and the roll angle. Time lag is described using a first-order differential equation.

With regards to the aerodynamics, this model includes variable drag coefficient and height of the centre of pressure, the point in which the aerodynamics forces are applied (Fig.2), described as particular functions of the longitudinal acceleration, and a fixed lift coefficient. Variable aerodynamics properties can strongly influence the different maneuvers that occur in a circuit lap, as shown by Bertolazzi, Biral [8]. In particular, they play an important role at the entrance and at the exit of a curve in order to reach the maximum deceleration and acceleration, avoiding stoppies and wheelings.

The control inputs are the front and the rear longitudinal forces and the steering torque applied to the handlebar.

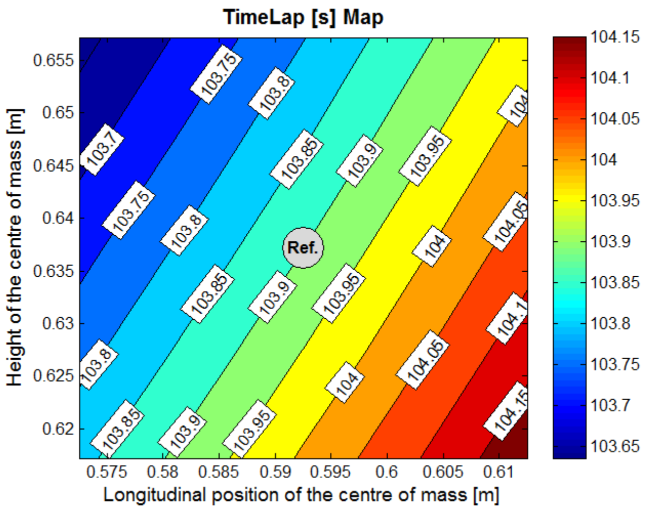

Fig. 6. Map of the lap times due to the variation of the position of the centre of mass of the vehicle in DRY conditions.

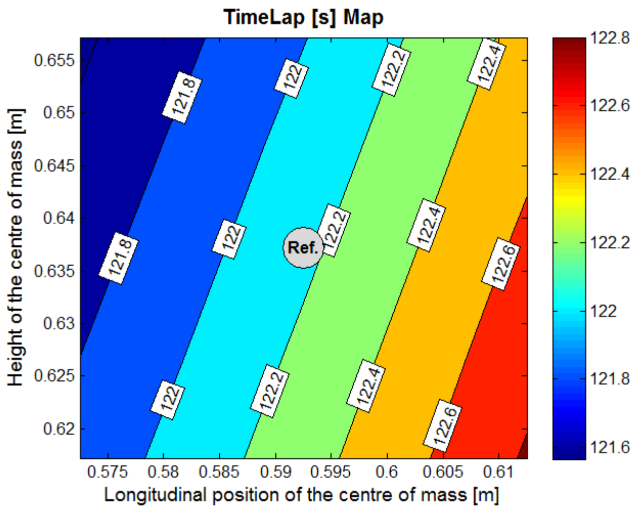

Fig. 7. Map of the lap times due to the variation of the position of the centre of mass of the vehicle in WET conditions.

Regarding the road scenario, it is described in curvilinear coordinates as a list of segment of given lengths and curvatures.

III. DRY AND WET RIDING

In this section a comparison between the "Optimal Maneuver Method" results and real telemetry data is presented. The results are referred to a test lap on the international circuit of Valencia (Comunitat Valenciana Ricardo Tormo Circuit), represented in Fig.4, 4005m of length and 12m of width, performed by a 125cc motorcycle and a professional rider in both dry and wet conditions. The same scenario is computed by means of the "Optimal Maneuver Method" using a motorcycle of the same category of the one used for tests. Regarding tire adherence, it does not exists any reliable method for an a priori estimation of the actual adherence limits of racing tires, and tuning adherence coefficients from g-g diagram is perhaps the only possibility available. However, g-g diagrams actually express a combination of tire adherence and rider skills and therefore the more skilled is the rider, the more reliable is the estimation of adherence.

The chosen longitudinal and lateral coefficients of adherence are reported below:

DRY conditions:	D_longitudinal	= 0.950
	D_lateral	= 1.375
WET conditions:	D_longitudinal	= 0.715
	D_lateral	= 0.900

Fig.3 and Fig.5 presents a comparison between the main observed variables of the simulation: the longitudinal speed, the longitudinal acceleration and the roll angle of the vehicle in both dry and wet track, and telemetry data.

The accordance between the telemetry and the simulations is quite evident for all the observed variables. Furthermore, if we compare the lap performed on the wet track with the one performed on the dry one it's possible to notice how: even though the roll angle of the vehicle decreases drastically of about 10 degrees and the negative part of the longitudinal acceleration (i.e. braking condition) decreases too, the positive longitudinal acceleration (i.e. driving condition) do not presents particular differences for most of the parts of the track. This fact is ascribable to the low power of the considered motorcycle and has interesting effects on the longitudinal speed: although the positive longitudinal accelerations are comparable, the maximum speed reached in most of the part of the track is lower for the wet conditions. The reason of that is the less efficient braking that obliges the rider to start braking before with respect to the dry conditions.

Regarding the minimum speed in the centre of each turn, it mostly depends on the roll angle, so for the wet conditions is always lower than for the dry ones.

A. Optimization of the CoM position

In order to perform an optimization of the position of the centre of mass of the vehicle, in both dry and wet conditions of the road, a parametric analysis has been carried out.

The choice of this parameter is due to its paramount importance and to the possibility of adjusting it in real races.

The height h and the lateral position b of the centre of mass have been changed as follows:

h : 0.6172m : 0.0100 : 0.6572m
b : 0.5725m : 0.0100 : 0.6125m

Two maps of the resulted lap times for the different configurations are presented in Fig.6 and Fig.7. The first thing that can be notice is how the trend in the two maps is quite similar. The minimum lap time is performed in both cases by the motorcycle in which the centre of mass is set on the highest and most backward position.

Since the whole track is considered, the reasons of such maps have to be studied in both acceleration and braking maneuvers.

With respect to acceleration, as Cossalter et al. [9] have shown, the limit between the two possible behavior of a motorcycle: the wheeling and the skidding of the rear tire, is mostly due to the longitudinal adherence tire coefficient and to the ratio b/h, between the longitudinal and the vertical position of the centre of mass. For the standard settings of the considered motorcycle the ratio b/h = 0.930 and compared with the peak of the adherence at the rear tire in both wet and dry conditions: b/h < 0.950 (dry), b/h > 0.715 (wet).

This means that for the standard settings the limit of the longitudinal acceleration is represented by the skidding of the tire for the wet track and by the wheeling for the dry one. It is important to notice that, if a motorcycle is not powerful enough the wheeling can't spontaneously occur.

The limit of the acceleration for wheeling is given by:

$$x'' = g\, b/h \tag{6}$$

where g is the gravity acceleration.
That is 9.12m/s² for the reference position of the centre of mass and corresponds on 1242N of longitudinal force that is more than the engine can provide. Furthermore, if the worst situation for wheeling is considered (lowest b and highest h), the limit for the acceleration is 8.55m/s² that corresponds on 1164N of longitudinal force that is once again more than the engine's possibilities. According to this, the movement of the centre of mass upward and backward allows higher load transfers from the front wheel to the rear one and higher static loads on the rear wheel improving traction, without any problems of wheeling for both the conditions of the track. In addition, since in dry conditions there are not even problems of skidding of the rear wheel (in contrast to wet conditions), the optimal position of the CoM is mostly connected to the braking maneuvers.

Another important observation regarding the two maps is that the one which refers to the wet track presents more vertical lines than the other. This fact shows the more importance of the longitudinal position of the centre of mass for wet tracks with respect to the dry ones. The reasons of that can be found in the concept of optimal braking. In conditions of low adherence the repartition of the braking must change to perform the highest deceleration and to reach the skidding limit conditions on both the wheels at the same time as shown by Cossalter et al. [9]. Thus the use of the rear brake becomes more important than in standard conditions. The optimal repartition of the braking force due to the longitudinal adherence coefficient is shown by:

$$F_f / F = (b + \mu h)/p \tag{7}$$

$$F_r / F = ((p - b) - \mu h)/p$$

where:
F = total braking force
F_f = front braking force
F_r = rear braking force
p = wheelbase
μ = longitudinal adherence coefficient

For these reasons, on dry tracks the height and the longitudinal position of the CoM have about the same weight in order to reach the settings of minimum lap time, whereas on wet tracks the b parameter influences more the performance of the motorcycle because of a greater load on the rear wheel during breaking is requested.

IV. CONCLUSIONS

In this work the optimal maneuver method has been applied to a 125cc motorcycle and whole track scenario by means of minimum lap time simulations.

First of all, a comparison between the simulations results and real telemetry data, referring to a test lap performed by a professional rider and a motorcycle of the same category of the one used for the simulations, has been presented. The comparison has been applied on both dry and wet conditions of the track. This operation has allowed to validate the method once more. The comparison has shown good match between simulations and telemetry for all the observed variables, i.e. longitudinal speed, longitudinal acceleration, roll angle.

The results of laps on dry track and of those on wet track have been analyzed and some differences and analogies have been discussed. The comparison has shown a similar trend in longitudinal positive acceleration (i.e. driving conditions), and differences in longitudinal deceleration (i.e. braking conditions), roll angle and speed profile.

Furthermore, the "Optimal Maneuver Method" has been presented as a good tool for the optimization of some constants of the motorcycle geometry and inertial properties, i.e. the height and the longitudinal position of the centre of mass, on different track conditions, dry and wet (i.e. varying the longitudinal and lateral tire adherence coefficients).

The simulations have shown a similar trend with a minimum lap time reached in both the track conditions for a setting with the CoM placed in the most upward and backward position. In addition, a more influence of the longitudinal position of the centre of mass, on the minimum lap time, has been detected in wet conditions rather than in dry ones. This has been explicated thinking to the optimal braking for low adherence conditions, in which the ratio between front and rear braking must vary in order to obtain the maximum deceleration.

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APPENDIX 1: MAIN CONSTANTS OF THE MOTORCYCLE MODEL

A. *Vehicle*

Total mass (vehicle+rider)	136.191 kg
Centre of mass height h	0.6372 m
Centre of mass longitudinal position b	0.5925 m
Wheelbase p	1.2318 m
Normal trail an	0.0828 m
Caster angle ε	0.4182 rad
Rolling moment of inertia	13.659 kgm²
Yaw moment of inertia	19.533 kgm²
Pitch moment of inertia	29.995 kgm²
Mixed moment of inertia	1.665 kgm²
Front assembly yaw moment of inertia	1.165 kgm²
Aerodynamics centre height acceleration condition hcaACC	0.5200 m
Aerodynamics centre height braking condition hcaDEC	0.6808 m
Aerodynamics drag coefficient acceleration condition kdACC (0.5ρCdA)	0.116 kg/m
Aerodynamic drag coefficient braking condition kdDEC (0.5ρCdA)	0.215 kg/m

B. *Rear Tire*

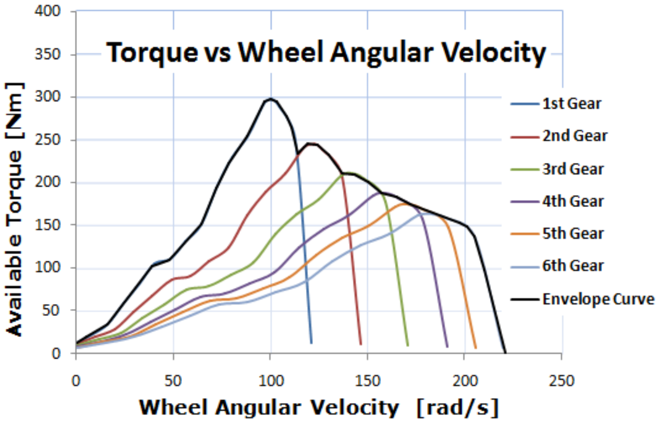
Rolling radius	0.300 m
Toroid radius	0.035 m
Non-dimensional side slip stiffness	10.6267
Non-dimensional roll stiffness	1.1174
Relaxation length	0.1348 m
Peak lateral coefficient of friction	1.375
Peak longitudinal coefficient of friction	0.950
Vertical stiffness	1.6e05 N/m

C. *Front Tire*

Rolling radius	0.285 m
Toroid radius	0.030 m
Non-dimensional side slip stiffness	10.032
Non-dimensional roll stiffness	0.840
Relaxation length	0.1000 m
Peak lateral coefficient of friction	1.375
Peak longitudinal coefficient of friction	0.950
Vertical stiffness	1.6e05 N/m

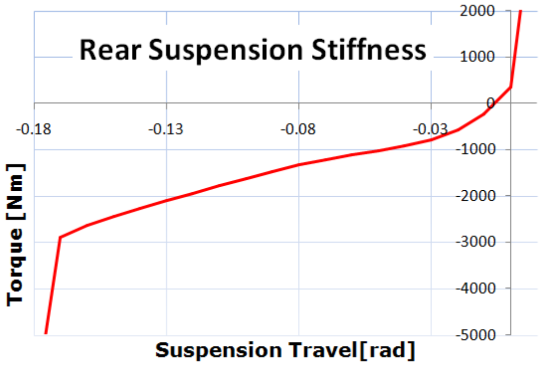
D. *Engine and Powertrain*

Engine torque available at the rear wheel:



E. *Rear Suspension*

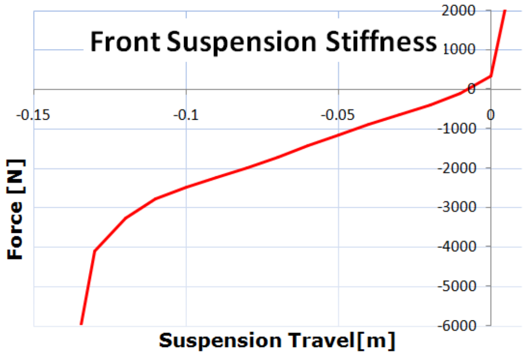
Torsion spring-damper system:



Compression linear damping coefficient	965.0 Nms/rad
Extension linear damping coefficient	784.2 Nms/rad

F. *Front Suspension*

Traditional spring-damper system:



Compression linear damping coefficient	2950.0 Ns/m
Extension linear damping coefficient	3089.0 Ns/m