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Application of the “Optimal Maneuver Method” for enhancing racing motorcycle performance

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ABSTRACT

The aim of this work is to improve the performance of a racing motorcycle by means of gearbox tuning. The *Optimal Maneuver Method,* which essentially simulates an ideal driver and computes the minimum *Lap Time* for a given motorcycle and a given circuit, is applied. A 1000cc SuperBike motorcycle and two very different racetracks, i.e. a fast one and a slow one, are considered. First the agreement between the *Optimal Maneuver Method* results and the logged telemetry data is proven, in order to fully justify its application. Next the relationship between gearbox ratio, lap performance and circuit characteristics is investigated and potential improvements are highlighted. Finally gearbox tuning is achieved by a *Lap Time* optimization procedure, and subsequent performance improvements are discussed.

INTRODUCTION

The design of a new racing motorcycle and the optimization of its performance is a long process that starts from the engineering specifications on maximum speed, handling indices, *Lap Time*, etc. and ends with the actual vehicle testing. The design process proceeds through many different steps of which on-road tests of a working prototype is among the most important. Many vehicle kinematic/dynamic quantities are monitored and compared with the initial specifications, of which *Lap Time* is a common performance index. Further prototype modifications and subsequent tests are necessary, and test-rider evaluations are often of paramount importance in order to guide the vehicle’s development. However, on-road tests are time and resource consuming. Hence it is convenient to use numerical simulations to identify a critical subset of parameters and plan the proper changes to work on. Numerical simulations are recognized as a useful tool provided that the mathematical model of the vehicle is well validated and a rider model is available. In fact, as in real life where test rider driving skill and sensitivity influence engineering direction, in simulations the rider model may affect the optimization results. In this sense an “ideal rider” should always be able to drive the vehicle at its maximum performance, adapting his driving style both to different vehicle dynamics (different equipment, different settings, etc.) and to different environmental situations (path geometry, surface adherence, etc.). To this purpose the *Optimal Maneuver Method* is proposed as an “ideal rider” [1,7,9], and constitutes the basis for the work presented in this paper.

In the following sections the *Optimal Maneuver Method* is applied in tuning the gearbox of a racing motorcycle. In the first section a brief description of its main features is presented. In the second section the comparison between *Optimal Maneuver Method* results and experimental data is illustrated in order to demonstrate its fidelity. Additionally the influence of the gearbox is examined by *Lap Time* simulations on different racetracks revealing potential improvements. In the last section an optimal gearbox configuration is obtained, and corresponding performance improvements are analyzed.

OPTIMAL MANEUVER METHOD

In this section a brief description of the *Optimal Maneuver Method* is presented detailing its basic principles and the underlying mathematical model.

BASIC PRINICIPLES – An “ideal rider” [6,7] should be able to drive the vehicle at its maximum performance, exploiting the road scenario (surface adherence, road geometry, etc.) and adapting its driving style both to vehicle dynamics (different settings and modifications) and to different environmental situations (path geometry, surface adherence, etc.). From the optimal control theory point of view [3], the simulation of a motorcycle minimum *Lap Time* problem can be posed as the constrained minimization of an integral target function (the *Lap Time* in this case) expressed by the following equation:

$$\int_0^L J(x(s),u(s)) \cdot ds \qquad (1)$$

where

s = curvilinear coordinate;
L = path length;
u = rider controls;
x = mechanical system state vector.

The constraints include the equations of motion of the rider-motorcycle system (eq. 2), the initial and final conditions (i.e. vehicle positions and velocities on the race track at the start and finish line, eq. 3) and a wide range of inequalities (eq. 4). The inequalities comprise the motorcycle physical limitations (tire force saturation, maximum engine torque, etc.), the track geometry and road surface adherence.

$$A(x(s))\dot{x}(s) - f(x(s),u(s)) = 0 \qquad (2)$$

$$\begin{cases} bci(x(0)) = 0 \\ bcf(x(L)) = 0 \end{cases} \qquad (3)$$

$$g(x(s),u(s)) \le 0 \qquad (4)$$

The result of the optimal control problem fully describes both the dynamics of the motorcycle-rider system during the minimum *Lap Time* maneuver (trajectory, speed, roll, etc.), and the rider inputs that produce the maneuver [2,8,9]. One of the main advantages of this method is that no “driving rules” have to be predefined (as in other approaches such as fuzzy logic or neural net); they emerge from the optimality criterion and from the solution of the control problem itself. As a second main advantage of the method, the scalar value of the integral (i.e. the *performance index*) yields an objective measure of vehicle performance on a specific race track. The *performance index* for a given motorcycle measures its intrinsic performance, i.e. the maneuverability, and in this sense can quantify the vehicle behavior. The method guarantees that if some design parameters (masses, frame geometry, gear ratios, etc.) are changed, the vehicle model is always driven at its maximum as if by an “ideal rider”. As a consequence, on the basis of the *performance index*, different motorcycles can be compared and the best design parameters can be identified [4,10].

MATHEMATICAL MODELS – The motorcycle model consists of four rigid bodies: the front and rear assemblies, and the front and rear wheels. The front assembly accounts for the front fork, the handlebar and the front wheel mass and diametral inertia. The rear assembly is composed of the engine, the rear frame, the swing arm, the rear wheel mass and diametral inertia, and the rider’s body. The front and rear wheels are included as pure moments of inertia about their spin axes. Thus, the motorcycle model has 5 degrees of freedom: forward speed, lateral speed, yaw angle, roll angle, steering angle. Tires are modeled with toroidal cross-section and generate three forces (i.e. longitudinal, lateral, normal forces) at the actual contact point. The lateral forces are modeled with a simplified version of the Pacejka formula, as a function of the sideslip angle and the wheel roll angle. Time lag is modeled using a first order differential equation. The suspension model is very simple and consists of a first order equation which approximates the time lag of load transfer between the front and the rear wheels due to the suspensions. The control inputs are the rear and the front tire longitudinal forces, and the steering torque applied on the handlebar. The road scenario is described in curvilinear coordinates as a list of segments of given length and curvature. For each segment the distance from the road center line to the left and right borders may vary.

GEARBOX ANALYSIS BY OPTIMAL MANEUVER METHOD

In this section the importance of the gear ratios and their dependence on the specific characteristics of the racing circuit (number and types of curves and straightaways) is examined. *Lap Time* simulations of a 1000cc SuperBike motorcycle are computed, and compared to telemetry data in order to demonstrate the fidelity of the simulated maneuvers. All motorcycle model parameters are specified based on accurate laboratory measurements and technical documentation (geometrical and inertial parameters, engine torque curve and tires properties are reported in the APPENDIX).

POWERTRAIN CHARACTERIZATION – The powertrain of the motorcycle is modeled by specifying the engine torque curve as function of RPM at full throttle (see the APPENDIX) and the velocity ratios of the transmission (Figure 1) as:

$$R = \frac{z_{driven}}{z_{drive}} \qquad (5)$$

where

z_{driven} = number of teeth of the *driven* gear;
z_{drive} = number of teeth of the *drive* gear.

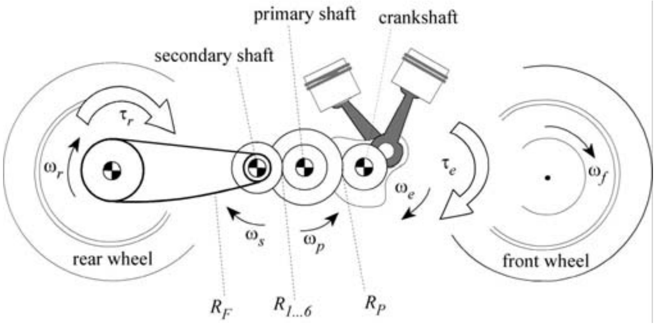

Figure 1 : Transmission layout (crankshaft - primary shaft - secondary shaft - rear wheel).

In the following table the velocity ratios of the transmission are listed in terms of the *primary ratio* (R_P between engine crankshaft and primary gearbox shaft), *gearbox ratios* (R_1 , R_2 , ...R_6) and *final ratio* (R_F between secondary gearbox shaft and rear wheel). Gearbox ratios are reported in their reference setting. In practice it is common to adjust gear ratios for a given circuit based on test laps or rider feedback.

Velocity Ratio	$R = \frac{z_{driven}}{z_{drive}}$
R_P (Primary)	73/47 (1.553:1)
R_1 (1st gear)	41/18 (2.278:1)
R_2 (2nd gear)	40/19 (2.105:1)
R_3 (3rd gear)	39/20 (1.950:1)
R_4 (4th gear)	37/22 (1.682:1)
R_5 (5th gear)	36/23 (1.565:1)
R_6 (6th gear)	34/25 (1.360:1)
R_F (Final)	42/17 (2.471:1)

Table 1 : Velocity ratios (“reference” gearbox).

Figure 2 shows the maximum driving torque available at the rear wheel at different vehicle speeds for each gearbox ratio, according to

$$\begin{cases} \tau_r = \tau_e \cdot \left(R_P R_i R_F \right) \\ \omega_r = \dfrac{\omega_e}{\left(R_P R_i R_F \right)} \qquad i = 1...6 \end{cases} \tag{6}$$

The thick grey line envelops the maximum thrust torque (i.e. full throttle) available at the rear wheel [5] at any forward speed. By selecting the proper gear ratio the *Optimal Maneuver Method* computes the maximum thrust torque at rear wheel according to the motorcycle velocity and engine characteristics. Of course the maximum available thrust force is not always used since some throttling may occur. In the next two sections the gearbox is examined through a full racetrack *Lap Time* simulation. The analysis is carried out in two very different circuits, in order to investigate the relationship between track characteristics and gearbox tuning.

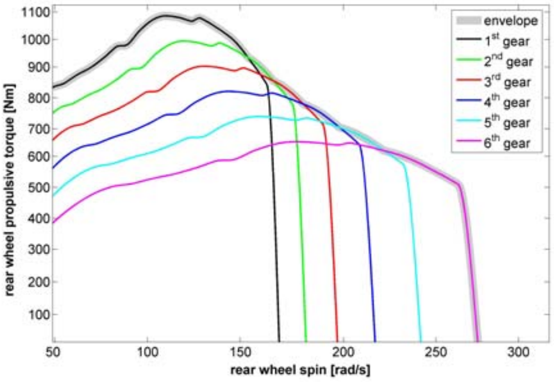

Figure 2 : Maximum available thrust torque at rear wheel (“reference” gearbox).

FAST RACE TRACK – Mugello circuit (Scarperia, Firenze, Italy) is one of the longest modern circuits (5.245 km), characterized by high speed chicanes, a mix of slow and high-speed corners, and a very long straight (1.141 Km). Mugello is a very technical track, but gearing is crucial in order to obtain maximum performance from the engine along the straight, since there is almost 950 m at full throttle. Figure 3 illustrates simulation with the optimal trajectory and corresponding *Lap Time* (116.169 s). The simulation consumed about ten minutes with a Pentium(R) 4, CPU 2.66 GHz - 1.00 GB RAM. Maximum speed (302.662 Km/h) occurs at the end of the straightaway and is followed by the greatest braking deceleration (-11.878 m/s^2) into the minimum speed curve (62.196 Km/h). Maximum acceleration (9.858 m/s^2) occurs at the exit of the next slow corner. While maximum roll angles (about 56 deg) occur in the high speed chicane which follows.

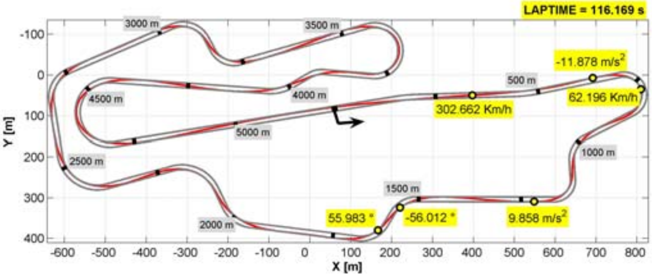

Figure 3 : *Lap Time* simulation overview for Mugello circuit.

Lap Time simulation correlation – In this section, in order to verify the theoretical basis and results of the *Optimal Maneuver Method*, comparisons with telemetry data acquired from an inertial measurements unit (three accelerometers and three gyrometers, with integrated GPS) is illustrated. Figure 4 compares the simulated forward speed, longitudinal acceleration and roll angle to the experimental channels. The agreement is quite good, and proves that the *Optimal Maneuver Method* is able to produce realistic racing maneuvers in one of the most representative fast racetracks. As such the following investigation regarding the relationship between gearbox ratios and lap performance is justified.

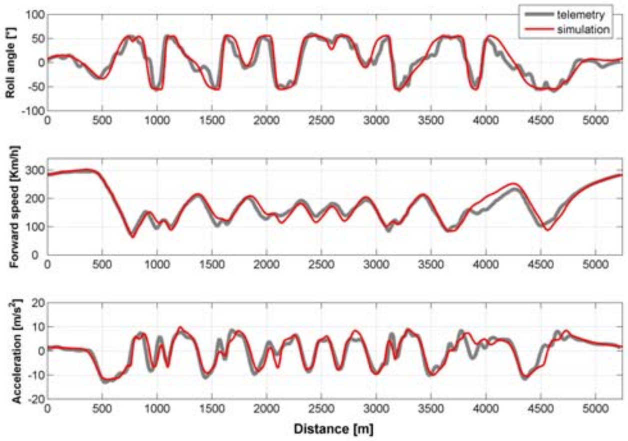

Figure 4 : Comparison between *Lap Time* simulation and telemetry for Mugello circuit.

Lap Time simulation analysis – Figure 5 superimposes the thrust torque actually used by the virtual rider in Mugello to the thrust torque envelope already represented in Figure 2. Comparing the used torque (circles) with the maximum available torque (continuous line), it is possible to distinguish two different ranges of speed. The lower one, involving *1st* gear, and characterized by the fact that the available thrust torque significantly exceeds that used. The higher range, involving the *2nd*, *3rd*, *4th*, *5th*, *6th* gears, is characterized by the fact that the applied thrust torque reaches the maximum available in certain phases. If this limit were higher, there would potentially be an advantage in terms of *Lap Time* performance. Also note that there may be a tangible advantage in the maximum speed if the *6th* gear ratio were higher, due to the very long straight that characterizes the circuit.

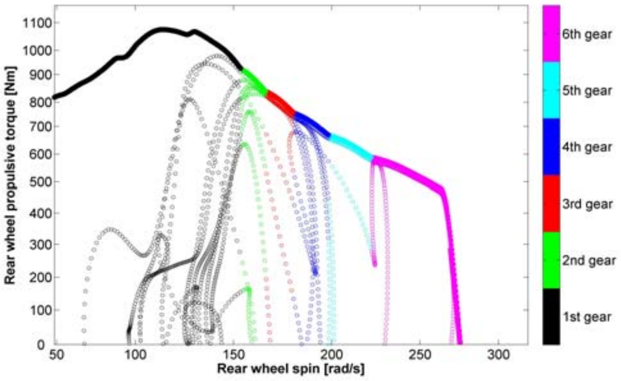

Figure 5 : Used thrust torque with respect to maximum available for Mugello circuit.

SLOW RACE TRACK – In contrast to Mugello, the Adria circuit (Adria, Rovigo, Italy) is one of the shortest modern circuits (2.702 km), characterized by many short straights (about 0.5 Km) followed by a sequence of slow variable-radius corners. Thus hard braking, quick changes in direction and good turning capabilities are required. Gearing is crucial in order to maximize engine performance in the acceleration phase of the numerous curve exits. Figure 6 illustrates the simulation results, including the optimal trajectory and corresponding *Lap Time* (82.986 s). The simulation required about seven minutes with a Pentium(R) 4, CPU 2.66 GHz - 1.00 GB RAM. The maximum straightaway speed (242.253 Km/h) is considerably lower than Mugello, and is followed by the greatest braking deceleration (-11.128 m/s^2). Maximum acceleration (10.770 m/s^2) occurs at the exit of the minimum speed corner (17.783 Km/h), which is quite slower respect Mugello. Maximum roll angles (about 55 deg) occur in an high speed chicane and in a high speed curve.

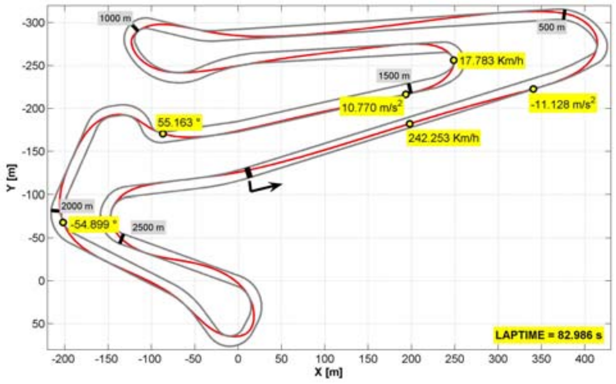

Figure 6 : *Lap Time* simulation overview for Adria circuit.

Lap Time simulation correlation – The comparison between the simulated forward speed, longitudinal acceleration and roll angle to the experimental channels is depicted in Figure 7. The agreement is good, and demonstrates that the *Optimal Maneuver Method* yields realistic racing maneuvers even in one of the most technically demanding, slow circuits.

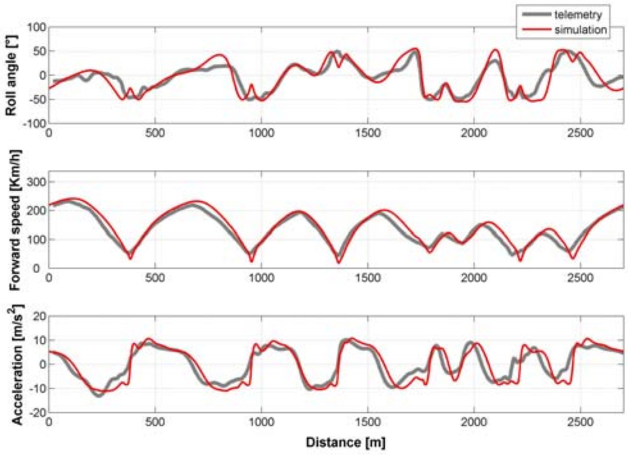

Figure 7 : Comparison between *Lap Time* simulation and telemetry for Adria circuit.

Lap Time simulation analysis – The following figure superimposes the thrust torque used by the virtual rider on the thrust torque envelope shown previously in Figure 2. Comparing the used torque (circles) with the maximum available torque (continuous line), it is possible to distinguish three different ranges of speed.

The lowest one, involving the 1^{st} gear, is characterized by the fact that the available thrust torque slightly exceeds the used one. The intermediate range, involving 2^{nd}, 3^{rd}, 4^{th} and 5^{th} gears, is characterized by the fact that in certain phases the thrust torque used reaches the maximum available limit. If this limit were higher, there would be probably a tangible benefit in terms of *Lap Time* performance, due to the higher acceleration capability. Finally, the highest range of speed, involving 6^{th} gear, is barely approached as a consequence of the short straightaway that characterizes the circuit.

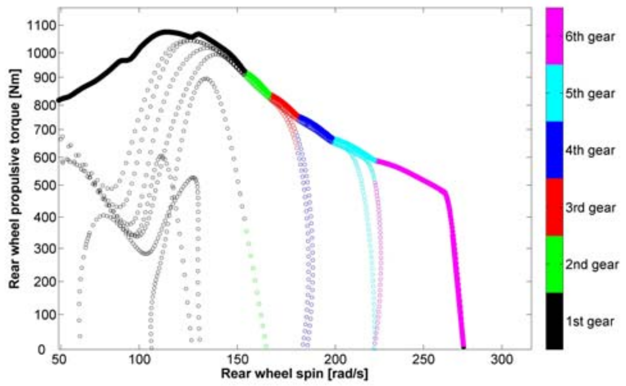

Figure 8 : Used thrust torque with respect to maximum available for Adria circuit.

GEARBOX TUNING BY OPTIMAL MANEUVER METHOD

In this section gearbox tuning will be enhanced by applying the *Optimal Maneuver Method*. Starting from the “reference” case simulated previously, an optimal gearbox configuration is obtained by minimizing *Lap Time*, and is further analyzed in order to demonstrate performance improvements.

MINIMUM PROBLEM FORMULATION – From a mathematical point of view, the gearbox tuning is formulated as a minimization problem. The terms are constituted by:

- the quantity to minimize, i.e. the *Lap Time* on a circuit (dependent variable);
- the parameters to vary, i.e. the gearbox ratios R_1, R_2, ... R_6 (independent variables);
- the function *f* relating the dependent variable to the independent variables, i.e. the *Lap Time* simulation computed by the *Optimal Maneuver Method*:

$$Lap\ Time = f\left(R_1, R_2, \ldots R_6\right) \tag{7}$$

- the mathematical method adopted to minimize the function *f* .

Regarding the parameters to vary, i.e. the gearbox ratios R_1 , R_2 , ... R_6 , the following guidelines have been considered. The distance (*I*) between the gearbox shafts (Figure 9) is related to the number of teeth *z* of each pair of interacting gears by the following:

$$I = \frac{D_{drive} + D_{driven}}{2} = \frac{m}{2}\left(z_{drive} + z_{driven}\right) \tag{8}$$

where *m* is the gear modulus.

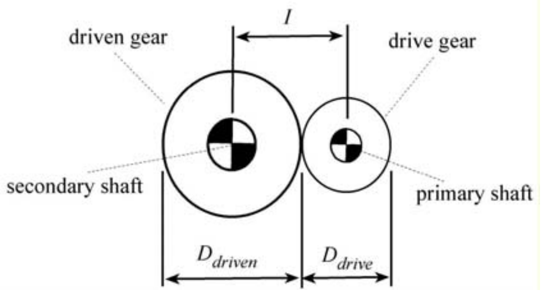

Figure 9 : Geometric layout of two interacting gears.

The 1^{st} gear ratio is not included in the optimization, because the simulation is a “rolling start” lap, whereas the actual motorcycle must commence from a zero velocity, “standing start”. Hence the 1^{st} gear ratio is fixed to that of the actual motorcycle. Further the modulus has been assumed the same for each pair of interacting gears. Consequently, according to Table 1, the previous equation can be turned into

$$z_{drive} + z_{driven} = \frac{2I}{m} = 59 \tag{9}$$

which bounds the number of teeth of each pair of interacting gears from 2^{nd} to 6^{th} velocity ratio (Figure 10).

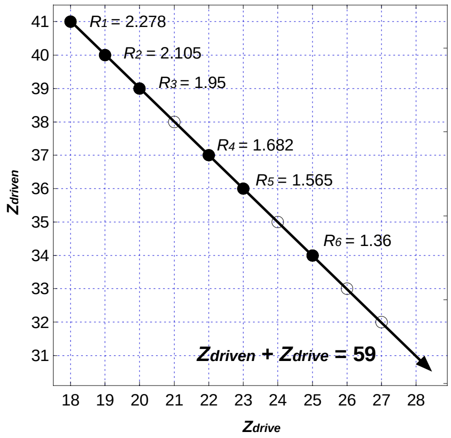

Figure 10 : Range of variation from 2^{nd} to 6^{th} velocity ratio.

Considering engine power limitation, the fastest gear ratio has been assumed equal to

$$R = \frac{32}{27} \tag{10}$$

Since the number of combinations is finite (about one hundred) each of them has been computed (extensive search), although a constrained optimization could also have been applied.

FAST RACE TRACK – The previous considerations regarding Mugello racetrack suggest to increase both the maximum speed (to obtain a greater performance on the long straight), and the thrust capability (to improve the acceleration phases).

Optimized gearbox - The following figure summarizes the results of the *Lap Time* optimization. The *2nd*, *3rd*, *4th* gear ratios are not modified; whereas the *5th*, *6th* are “taller” (for maximum speed). The performance improvement in term of *Lap Time* was simulated to be 0.312 s.

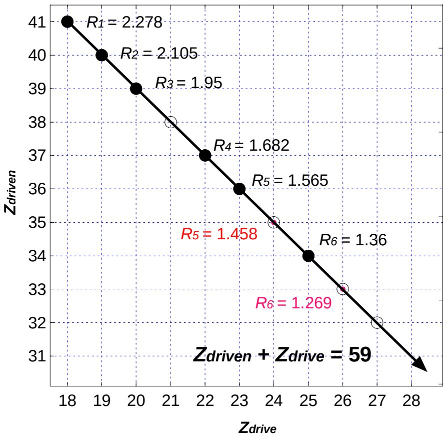

Figure 11 : Optimized velocity ratios for Mugello circuit.

Performance improvement analysis – The diagram with rear wheel propulsive torque is further considered in the following figure: the red case corresponds to the optimized gearbox, the black case to the reference gearbox. The higher range of speed obtainable with reduced *5th* and *6th* gear ratios is shown.

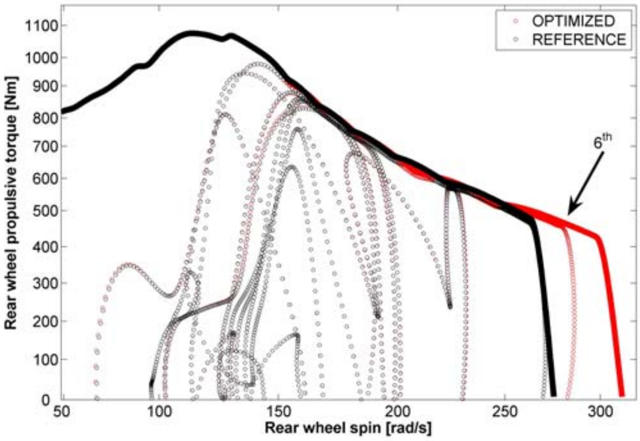

Figure 12 : Used thrust torque with respect to maximum available for Mugello circuit.

The next figure shows the improvement in forward speed of the optimized gearbox with respect to the reference case. It is evident that the greatest gain (10.75 Km/h, *6th* gear ratio) occurs along the main straight.

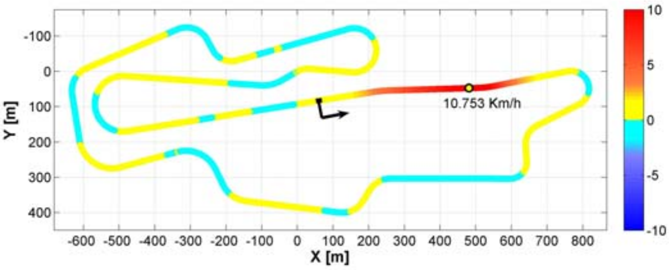

Figure 13 : Speed gain for Mugello circuit with the optimized gearbox.

SLOW RACE TRACK – The previous considerations regarding Adria racetrack suggest to increase the thrust capability to obtain greater performance in the acceleration phase at the exit of the numerous slow corners.

Optimized gearbox - The following figure summarizes the results of the *Lap Time* optimization. The *2nd*, *3rd*, are not modified; the *4th*, *5th* and *6th* are made “shorter”. The performance improvement in term of *Lap Time* was simulated to be 0.113 s.

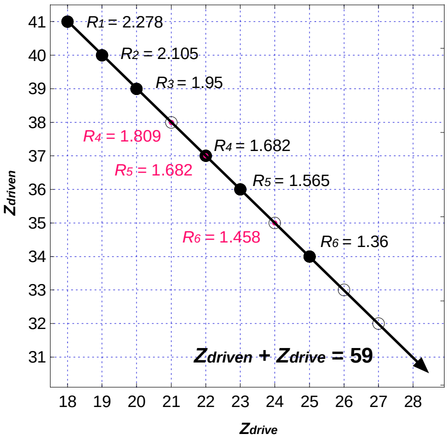

Figure 14 : Optimized velocity ratios for Adria circuit.

Performance improvement analysis – The following figure considers rear wheel propulsive torque. The red line corresponds to the optimized gearbox, while the black line represents the reference gearbox. The higher thrust capability available with increased *4th*, *5th*, *6th* gear ratios is apparent.

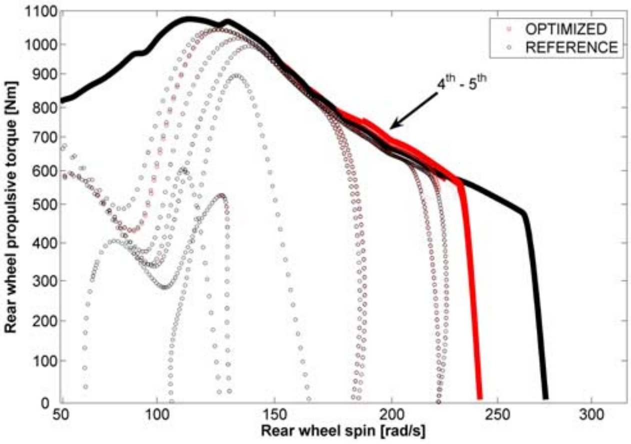

Figure 15 : Used thrust torque respect maximum available for Adria circuit.

In the next figure the improvement in forward speed of the optimized gearbox with respect to the reference is illustrated. It is evident that the greatest gain (7.36 Km/h, *4th* gear) occurs along the main straightaway.

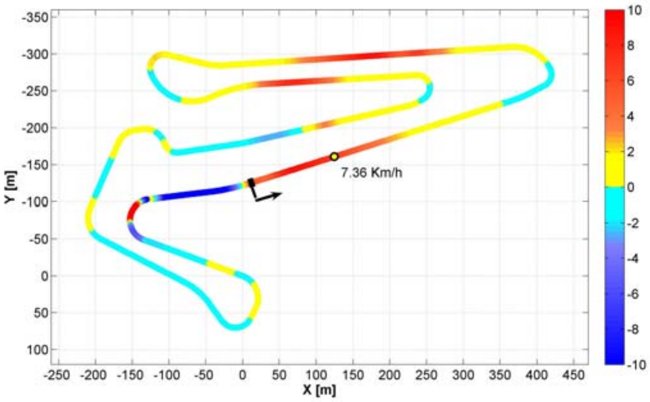

Figura 16 : Speed gain for Adria circuit with the optimized gearbox.

CONCLUSION

In this work the *Optimal Maneuver Method* has been applied. Effectively this method simulates an ideal driver and computes the minimum *Lap Time* for a given motorcycle on a given track. First its reliability has been shown by the comparisons of *Lap Time* simulation results with telemetry of a 1000cc SuperBike motorcycle. The agreement between calculated and measured quantities proved favorable even in racetracks with very different characteristics. Further the relationship between the gearbox of a 1000cc SuperBike, the racetrack characteristics and the *Lap Time* performance has been investigated. The fast circuit analysis has suggested the possibility to reach a higher maximum speed on the long straight. The slow circuit analysis has suggested the possibility to improve acceleration capability in exiting the numerous slow curves, and consequently run at higher speeds on the following short straights. Finally the *Optimal Maneuver Method* has facilitated the optimization of the 1000cc SuperBike gearbox. The *Optimal Maneuver Method* has proven quite reliable in computing realistic racing maneuvers as a means to improve gearbox tuning and hence racing motorcycle performance. Next steps will involve more detailed motorcycle models especially with regard to the description of the suspension systems.

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APPENDIX

Characteristics of the 1000cc SuperBike Motorcycle:

Vehicle		
Total mass (vehicle+rider)	262.517 *kg*	
CoM height	0.591 *m*	
CoM longitudinal position	0.729 *m*	
Wheelbase	1.445 *m*	
Normal trail	0.092 *m*	
Caster angle	25.038 *deg*	
Moment of inertia with respect to rolling axis	16.476 $kg\ m^2$	
Mixed moment of inertia	- 0.884 $kg\ m^2$	
Moment of inertia with respect to yaw axis	43.040 $kg\ m^2$	
Front wheel axial inertia	0.46 $kg\ m^2$	
Rear wheel axial inertia	0.664 $kg\ m^2$	
Front wheel diametral inertia	0.216 $kg\ m^2$	
Rear wheel diametral inertia	0.333 $kg\ m^2$	
Front wheel rolling radius	0.295 *m*	
Rear wheel rolling radius	0.307 *m*	
Rear wheel cross section radius	0.094 *m*	
Front wheel cross section radius	0.059 *m*	
Aerodynamic drag coefficient, $\frac{1}{2}\rho C_d A$	0.2 *kg/m*	
Rear tire		
Rolling radius	*0.307 m*	
Toroid radius	*0.095 m*	
Non-dimensional sideslip stiffness	11.43 *1/rad*	
Non-dimensional roll stiffness	1.242 *1/rad*	
Relaxation length	0.152 *m*	
Maximum lateral coefficient of friction	1.3	
Maximum longitudinal coefficient of friction	1.3	
Front tire		
Rolling radius	*0.295 m*	
Toroid radius	*0.065 m*	
Non-dimensional sideslip stiffness	12.16 *1/rad*	
Non-dimensional roll stiffness	1.078 *1/rad*	
Relaxation length	0.085 *m*	
Maximum lateral coefficient of friction	1.25	
Maximum longitudinal coefficient of friction	1.25	
Engine		
Power	*131.8 KW* / 11500 *RPM*	
Engine torque curve	4000 *RPM*	95.37 *Nm*
	4500	97.14
	5000	100.14
	5500	102.60
	6000	105.97
	6500	110.04
	7000	111.27
	7500	116.57
	8000	120.21
	8500	121.55
	9000	120.98
	9500	119.63
	9880	120.66
	10500	117.32
	11000	114.16
	11500	109.46
	12000	103.32
	12500	96.64
	13000	88.30
	13500	81.70