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TEAM ASPAR Uses Binary Optimization to Obtain Optimal Gearbox Ratios in Motorcycle Racing

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In this paper, we present a binary integer linear program for obtaining the optimal combination of gears to install on a competitive racing motorcycle. Our objective is to meet the requirements of both the rider and track at a set of points on the racing circuit. This requires determining the best transmission (gearbox) for each circuit and rider. We discuss a solution for a rider in the World Motorcycling Racing Championship.

Key words: integer programming; gearbox.
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TEAM ASPAR, a Spanish team in the World Motorcycle Championship, is one of the world's most successful motorcycle-racing teams. It boasts the following successes: two world championship titles, three world championship runner-up titles, two European titles, and six Spanish national titles. The World Motorcycle Championship, the premier championship event of motorcycle road racing, has three categories (note that cc refers to cubic centimetres): 125 cc, Moto2 (600 cc), and MotoGP (1,000 cc). The 125 cc category uses a two-stroke engine; Moto2 and MotoGP use four-stroke engines. The 2010 racing calendar consisted of 18 rounds in 16 countries. A team that participates in one of this competition's three categories usually includes two riders with two bikes for each rider (note that we use the terms motorcycle and bike synonymously); each rider is supported by engineers, technicians, and telemeter (i.e., data acquisition and analysis) specialists, mechanics, and auxiliary personnel. Depending on the category in which it is competing, this section of the team can range from 6 to 10 people per rider. The team also includes members of the press and media, the coordinating team (i.e., staff members who coordinate team sponsorships, scheduling, and marketing), and the catering and hospitality staff, bringing the number of team members to between 20 and 30 people.

The tasks and operations that a team, particularly TEAM ASPAR, must perform are described as follows. The work plan commences at the beginning of each race, the Grand Prix (GP), which is the Motorcycling World Championship. From the arrival of the bikes, tools, and hospitality staff at the circuit until the day of the race, a six-day project is put into action; during this period, team members perform hundreds of meticulously ordered and sequenced tasks. During the first three days, the technical staff and the riders performs their tasks separately; however, during the final three days prior to the GP, they do most tasks together.

On the third day prior to the GP, technical staff members unpack the motorcycles from the boxes used to transport them to the race location and clean them for exhibition in the pits. The technical engineers review the telemetric data for the GPs that have taken place at the same circuit in previous years. If the GP is being held at a new circuit and previous data are not available, the technical staff proceeds to study the characteristics of the track layout (e.g., bend radius, approximate passing speeds, length of the straights, and variations in the track gradients). Simultaneously, the mechanics responsible for each motorcycle strip down the bike and engine. They meticulously follow the instructions of the engineers and technicians to thoroughly check the bike's mechanical and electrical parts and replace them as required (e.g., because of wear, mileage, or risk of possible faults). They then reassemble all the parts and configure and adjust the settings according to the most appropriate a priori guidelines; these settings will be used as a gearbox-configuration starting point at the beginning of the GP trials (i.e., practice races).

The optimization system we present in this paper, which helps TEAM ASPAR to determine the optimum gearbox configuration, provides the team with a significant advantage over teams that do not have the model at their disposal. A technician must select the best combination of gear assemblies, which constitutes the gear changes from several hundred thousand possible combinations. An ideal system should consider constraints that the mechanical engineer establishes, the engine torque, and the rider's preferences. This last aspect is fundamental in achieving a competitive advantage. Selecting a bike's optimal gear change can affect the motorcycle's behaviour; the gear change occasionally involves changes in the geometrics of the bike's electrical cycle. The team has little time to make modifications during a practice race. Therefore, establishing certain thresholds with regard to the maximum speeds per gear and the length between the rear wheel axle and the engine is necessary, as is analyzing these thresholds. Such analyses must depend on the value of each solution, as assessed by the engineer responsible for the task. To the best of our knowledge, the only other paper that addresses gearbox configuration selection is Savaresi et al. (2008); the authors present an approach that simulates the lap time for a given gearbox option. We are not aware of any papers that focus on optimizing gearbox ratios for motorcycle racing.

We organized this paper as follows. In the *Problem Description* section, we present the main aspects of the problem and its importance. In the *Gearbox Ratio in Motorcycle Racing* subsection, we discuss some characteristics of the gearbox in a competition motorcycle. In *Problem Formulation and Solution*, we introduce the binary integer (0-1) model for optimizing the gearbox ratios by using an example. In the final section, *Conclusions*, we discuss the results of this work and draw some conclusions. The appendix gives the mathematical model.

Problem Description

In professional motorcycle racing, a small improvement can be crucial in determining the final outcome of a race or championship; on many occasions, only a few thousandths of a second has separated a rider or team from competitors. Optimizing the gearbox design can allow a rider or team to achieve better performance when competing against others whose engines have the same mechanics.

Our optimization system allows a team to determine the ideal gear changes during each practice session and, more importantly, during the race to achieve maximum performance from the bike, and thus the best lap time. The model is based on data obtained from motorcycle data acquisition systems (i.e., data recording telemetry). The judgement and experience of the technicians and riders regarding the speed in taking a bend, the regime for the ideal engine revolutions at each point (torque engine), and the gear engaged are also important.

A typical automotive gearbox system consists of gears, shafts, bearings, and housings. Predicting gear vibration and noise has been a major concern in gear design. Recently, greater emphasis has been placed on further optimizing the gear-tooth parameters to reduce transmission error. Fonseca et al. (2005) present a genetic algorithm approach to minimize transmission errors of automotive spur gear sets. Abuid and Ameen (2003), Deb and Jain (2003), Dolen et al. (2005), Huang et al. (2005), and Savsani et al.

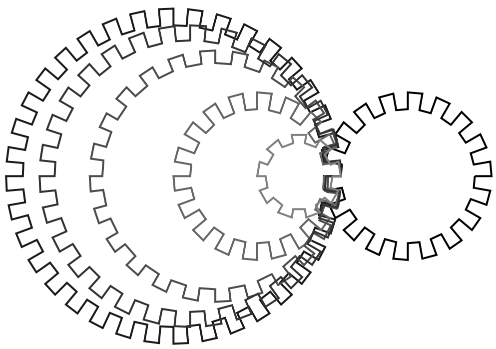

Figure 1: In this figure, the left gear has 60 teeth and the right gear has 18. Therefore, the gear ratio is 18/60 or 1/3.33 (also written as 1:3.33). The first number in the ratio is the gear receiving power from the engine (i.e., driven gear). For each revolution of the right gear, the left makes 1/3.33, or 0.3, revolutions.

(2009) analyze optimal gear design, including different objective functions. These objectives are related to dynamic factors caused by gear-teeth meshing, which are also related to the gear volume, weight, teeth, and distances.

In this paper, we discuss the selection of the best gearbox (i.e., the set of gear options available) for a given circuit. In designing a gearbox configuration, the gear ratio is a priority element.

Gearbox Ratio in Motorcycle Racing

The gear ratio is the relationship between the number of teeth on two gears that are meshed or two sprockets connected using a common roller chain, or the circumferences of two pulleys connected by a drive belt (see Figure 1).

Motorcycle drivetrains generally have two or more areas that use gearing: one is the transmission, which contains a number of different sets of gears that can be changed to allow a wide range of vehicle speeds; the second is the differential, which contains one additional set of gearing that provides an additional mechanical advantage at the wheels. These components can be separated and connected by a driveshaft, or they can be combined into one unit called a transaxle. Several parts in which demultiplication (to reduce revolutions) can be carried out are between the engine and the rear wheel (see Figure 2).

Only two of these parts are potentially subject to optimization—the gearbox and the secondary transmission, although they may affect each part that is involved in reducing the engine revolutions. Changing other components, although possible, cannot be done in a reasonable time; therefore, new combinations are tested only in these two locations. The number of potential combinations that can be tried by changing the cogs on the gearbox and transmission gives rise to the use of combinatorial optimization as an effective mechanism for obtaining solutions, which are later analyzed in the circuit.

Testing a great number of these combinations in competition is not feasible because of the limited number of days of practice runs. Thus, using a mathematical model to find the optimum combination can provide a great advantage to a team. We must also consider that not all possible combinations provide a feasible gearbox and secondary transmission for a competition motorcycle. At present, TEAM ASPAR works with approximately 40 second transmissions, 50 options for each gear, and six gears ($40 * 50^6$ combinations). For each option in the second transmission, a set of options is allowed for each gear in the gearbox. Note that a competition gearbox has approximately 13 million ($40 * 8^6$) combinations.

For each pair of transmission and gear options, we can calculate the reduction ratio and then obtain the velocity of a bike for a given engine revolution (see Figure 2). However, notice that the number of *transmission-gear* configurations that we need to evaluate is approximately 1,920 ($40 * 8 * 6$)—the number

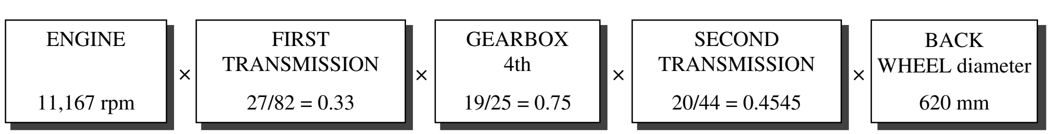

Figure 2: The diagram shows an example of gear ratio reduction in a competition motorcycle—from 11,167 revolutions per minute (rpm) of engine to 146.8 kilometers per hour (Km/h) of linear velocity in the motorcycle (146, Km/h $= 11{,}167$ rpm $\times\, 0.33 \times 0.75 \times 0.4545 \times 620$ mm $\times\, \pi/r \times 1$ Km/10^6 millimeters(mm) $\times\, 60$ min/h).

of second transmissions × the number of gear options for each transmission × number of gears.

In motor sports, an important gearbox characteristic is that explosive torque changes at lower revolutions per minute (rpm) may cause the rear tire to spin, unless the rider uses a higher rpm in which torque changes are less severe. This consideration also affects gear selection for a circuit, which is an essential element in setup before and during practice and qualification races. A close-ratio transmission is one with relatively little difference between the gear ratios of the gears. For example, a transmission with an engine shaft to driveshaft ratio of 4:1 in the first gear and 2:1 in the second gear would be considered wide ratio when compared with another transmission that has a ratio of 4:1 in the first gear and 3:1 in the second—the close ratio. In the wide-ratio example, the first gear is 4 (4/1) and the second gear is 2 (2/1); therefore, the transmission-gear ratio is 2 (4/2 or 200 percent). For the close-ratio the first gear is 4 (4/1) and the second gear is 3 (3/1); therefore, the transmission gear ratio is 1.33 (4/3 or 133 percent). However, all transmissions do not start out with the same ratio in the first gear or end with the same ratio in the fifth or sixth gear; thus, a comparison of wide-ratio and close-ratio transmissions is difficult.

Figure 3 depicts a six-speed manual transmission for a 125 cc competition motorcycle.

Close-ratio transmissions are generally used in motor sports in which the engine is tuned for maximum power in a narrow range of operating speeds and the driver can be expected to enjoy shifting frequently to keep the engine in its power band. Table 1 shows a realistic close-ratio transmission for a 125 cc motorcycle competition.

Gear	Ratio
1st gear	1:2.083
2nd gear	1:1.785
3rd gear	1:1.600
4th gear	1:1.375
5th gear	1:1.263
6th gear	1:1.117

Table 1: In a competition, a motorcycle uses a close-ratio transmission—a small gear ratio difference between two consecutive gears. The table shows a realistic example for the racing circuit of Jerez, Spain.

A close-ratio transmission allows the engine to always turn near its maximum power band when the rider shifts gears. Suppose that a given engine's power band lies between 7,000 and 8,000 rpm; shifting up from a 1.15 gear to a 1.0 gear represents only a 13 percent drop in the engine revolution speed. Executed at 8,000 rpm, the shift will achieve nearly 7,000 rpm—the low end of the engine's power band—and will allow the bike to continue accelerating quickly. Table 2 shows a realistic drop in engine revolution speed in a close-ratio transmission, for the transmission shown in Table 1. Notice that the engine revolution reduction can be obtained by the relationship depicted in Figure 2.

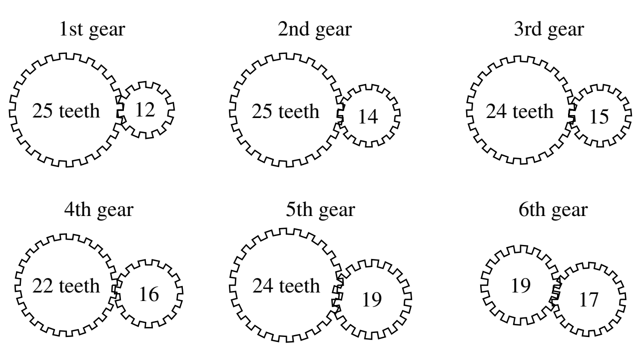

Figure 3: The diagram shows a set of possible gear options in a motorcycle competition.

Solutions Based on Experience

Prior to using our optimization tool, TEAM ASPAR did some simple calculations for a given second transmission and a maximum velocity for each gear. Its engineers calculated the gear options that would allow the required speed to be reached. However, the solution they obtained was not always optimal because it did not provide a close-ratio transmission.

Shift	Ratio difference	Drop in rpm
1st gear to 2nd gear	0.08015	1,457.22
2nd gear to 3rd gear	0.06477	1,177.74
3rd gear to 4th gear	0.10227	1,859.50
4th gear to 5th gear	0.06449	1,172.59
5th gear to 6th gear	0.10349	1,881.64

Table 2: The table shows the drop in engine revolution speed in a close-ratio transmission; the maximum engine revolution is 13,200 rpm.

By applying their experience and making small modifications, they were able to obtain a close-ratio gearbox with speeds near to those required; however, the solution was still not optimal.

Problem Formulation and Solution

TEAM ASPAR's Problem

An important feature of our gearbox-design model is the consideration of a significant set of points in the circuit; we refer to these as "brake points" and "acceleration points"—points at which the rider shifts down or up, respectively. At each point, a gear option, velocity, and revolutions are required. Brake points are related to the velocity through the curve; acceleration points are related to the velocity at the exit curve (i.e., point of maximum acceleration). See Figure 4.

For each gear in each second transmission, the engine revolutions necessary to reach the required speed must be evaluated at a given point on the circuit. From the calculations in Figure 2, we can determine the number of transmission gear configurations required to be 1,920 ($40 * 8 * 6$). The revolutions of the engine should remain in the power band to allow the motorcycle to achieve top performance.

The appendix shows the complete model that we used to solve TEAM ASPAR's problem. We outline the problem as follows (see the diagram in Figure 5).

A_1–A_{11} and B_1–B_{11} represent the acceleration and braking points considered. Table 3 shows the gear, rpm, and required speed (km/h) at these points.

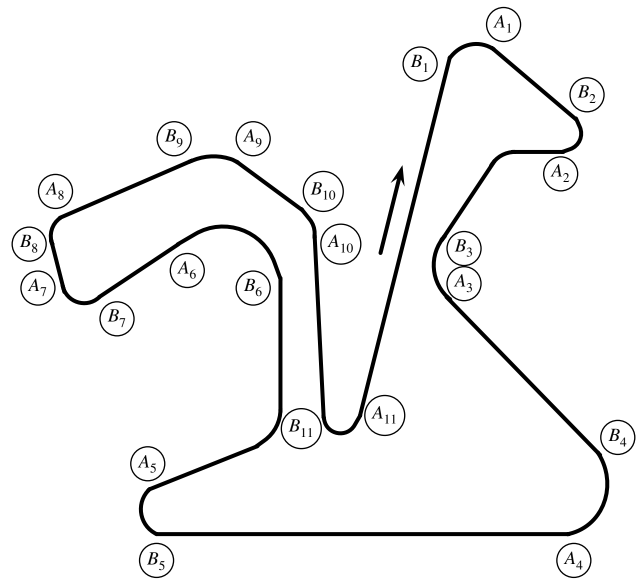

Figure 4: The diagram shows the Jerez racing circuit with the 22 significant braking and accelerating points that we considered.

The engineers considered 22 significant points on the circuit, points at which the rider needs a particular gear option and a minimum and maximum threshold for the revolutions reached by the engine. Note that the number of points to consider depends on the features of the circuit and the rider's needs. The example we show in Table 1 is the solution.

We implemented our models in a C++ environment using the optimization engine, CPLEX v11.0, and solved them on a computer with a 2.33 Ghz Intel

Brake				Accelerate			
Point	Gear	rpm	km/h	Point	Gear	rpm	km/h
B_1	6th	(12,750, 12,850)	208	A_1	2nd	(10,100, 10,250)	110
B_2	3rd	(13,100, 13,400)	138	A_2	1st	(9,300, 9,450)	86
B_3	5th	(12,650, 13,100)	155	A_3	5th	(12,450, 12,850)	141
B_4	6th	(12,200, 12,350)	198	A_4	4th	(10,200, 10,400)	135
B_5	6th	(13,400, 13,580)	219	A_5	1st	(8,300, 8,500)	75
B_6	5th	(13,100, 13,400)	179	A_6	4th	(11,050, 11,300)	142
B_7	5th	(12,150, 12,400)	161	A_7	2nd	(10,350, 10,600)	115
B_8	3rd	(11,600, 11,900)	131	A_8	3rd	(10,850, 11,000)	126
B_9	5th	(12,400, 12,400)	168	A_9	5th	(11,850, 12,100)	161
B_{10}	5th	(12,700, 13,100)	177	A_{10}	5th	(12,200, 12,500)	168
B_{11}	5th	(13,250, 13,400)	180	A_{11}	1st	(9,200, 9,350)	85

Table 3: The table shows the braking and accelerating points considered in the Jerez racing circuit.

Number of constraints	545
Number of 0-1 variables	2,369
Number of nonzero elements in constraint matrix	12,704
Density of constraint matrix	0.9%

Table 4: The table shows the model dimensions for the Jerez circuit problem.

Xeon processor, 8 Gb of RAM, and the Linux Enterprixe 3 operating system. The elapsed time required to solve the Jerez circuit instance (see the dimensions in Table 4) was approximately eight minutes, including data preprocessing, model generation, and optimization.

Model Impact

Following the solution's implementation and testing on the track, a rider's requirements (e.g., for a specific speed, number of revolutions, or gear to be engaged at a specific point on the circuit to provide a competitive advantage) may become clear. Modifying the model for a specific point on the circuit by necessity modifies the behaviour at the rest of the points, in addition to modifying the ratio between the gears. With the application of the 0-1 model, changing the specifications at a point on the circuit allows us to easily obtain a new solution, which continues to be valid for all points on the circuit and maintains ratios between the gears that make up a closed gearbox. This point is important for the riders because they frequently reject good solutions in the circuit in favor of solutions that are worse, but that provide an advantage at a particular point of the circuit.

Another advantage of this model is its ability to generate a robust gearbox configuration for uncertain conditions, as the following examples illustrate.

- A race in a new circuit about which the engineers have no previous gearbox configuration. The model allows a first configuration of the gearbox using the estimation of velocity in each curve. However, we point out that this situation is unlikely to occur.
- A variation of a known circuit (i.e., variation in some set of curves implies variation in the gear, rpm, and required speed at these curves.)
- Technological advances. Such advances can imply superior speeds in curves, thus requiring a new gearbox configuration.

We tested our model using the Jerez circuit. We began by measuring the speed at the curves and the engine rpm values at different points of the circuit. We then obtained the results of the best lap time obtained by a rider at this circuit by using TEAM ASPAR's standard solution, and used them as the input values in our model. The optimization model provided the gearbox that had been used in this best lap. Our models' solution proved to be a good starting solution for the engineers and riders, and was close to the race configuration gearbox used in the GP race.

The optimization software is user friendly in that it allows the final user (i.e., engineer) to enter different model parameters, such as wheel diameter, first transmission, and minimum and maximal gear ratio difference allowable for each gear, and shows the results via an easy-to-understand graphical user interface (see Figure 5).

The software allows the engineer to obtain the best six solutions for each instance of the problem by using a cut-appending scheme. This feature makes it easier for the engineer to determine the degree of validity and credibility of the model's solution. For each of the six solutions, the gear and rpm values at selected points of the circuit are shown, as well as the desired rpm values, which are specified as input. The engineer, for example, can select the solution that requires the fewest changes to the bike from these six solutions.

Conclusions

In this paper, we present a binary integer model for the multispeed gearbox design in motorcycle competitions. The model has been shown to work very well in selecting the best gearbox for a competition because it provides a robust solution that meets the needs of both the rider and motorcycle on each circuit. Using reasonable computing time, the rider's team can verify the validity of the model's solution, given the small changes in the rider's requirements at each point on the circuit.

TEAM ASPAR uses the results of our model five or six times in each race, and its engineers have seen an improvement of between 0.4 and 0.6 seconds per lap. They believe that using the model helps take advantage of the circuit characteristics (e.g., slopes in the circuit where greater engine power is necessary) and ensures the motorcycle's readiness.

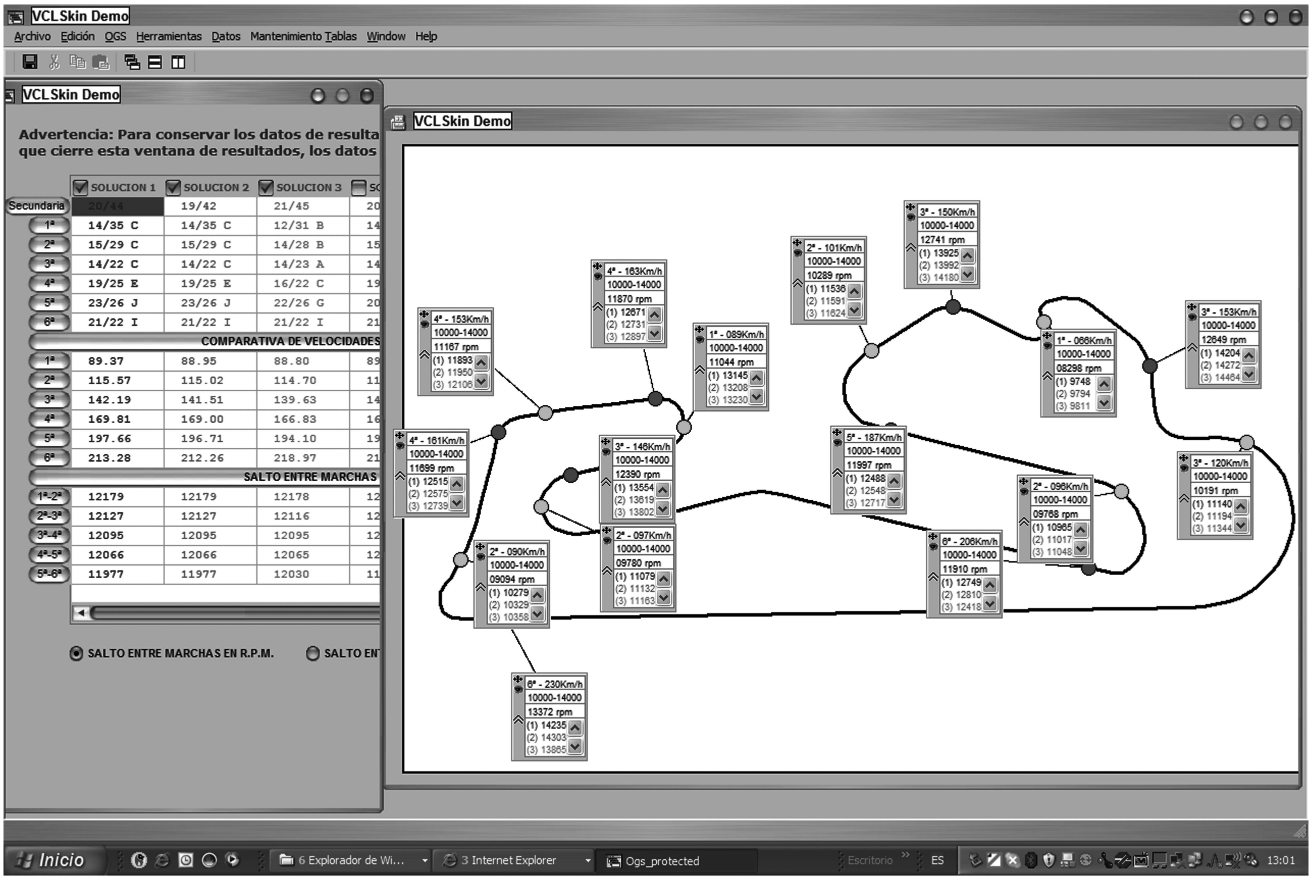

Figure 5: The software developed for TEAM ASPAR shows the six best solutions for the problem and the velocity for each solution in each significant point of the circuit.

Note that the problem dimension depends only on the number of braking and accelerating points considered, which are at most 24 in all the racing circuits. For each racing circuit, the 0-1 models have practically the same dimensions and structure; they differ only in the w_{ij}, objective function parameters (see the appendix). This feature allowed us to develop an effective algorithm that can be applied to any circuit.

Two future research projects are worth considering. The first is a study about defining new combinations in the gearbox—introducing a new set of variables to allow us to determine new options in the gearbox to manufacture it preseason. The second involves considering a new set of 0-1 variables in the model. These variables relate to the first transmission and back-wheel diameter, thus ensuring better solution values.

Appendix. Mathematical Model

The model presented here is a type of 0-1 linear-optimization problem. Wolsey (1998) and Jünger et al. (2010) provide a good exposition of integer optimization approaches of similar problems. The notation for the parameters and variables follows.

Sets of Elements

I: set of gears, $I = \{1, 2, 3, 4, 5, 6\}$.
J_i: set of options in gear i, for $i \in I$.
G: set of second transmissions.
J_i^g: set of options in gear i that belong to transmission g, for $g \in G$, $i \in I$. (Note that $J_i^g \neq \{\varnothing\}$, $J_i^g \cap J_i^{g'} = \{\varnothing\}$, g, $g' \in G$: $g \neq g'$.)

Parameters

c_{ij}: gear ratio for option j in gear i, for $j \in J_i$, $i = 1, 2, \ldots, |I| - 1$.
w_{ij}: mean deviation of the *rpm* of option j in gear i from the ideal rpm (see Table 3) for $j \in J_i$, $i \in I$. Note that the rpm values are calculated to obtain the ideal speed at each circuit point where gear i is required.

u_i, U_i: minimum and maximum difference, respectively, allowed between the gear ratio for the gears i and $i+1$, respectively, for $i = 1, 2, \ldots, |I| - 1$. These parameters are related to a close-ratio transmission and are provided by the engineers as a minimum and maximum drop in engine revolution speed (in rpm). Table 2 shows the relationship between both concepts.

Variables

x_{ij}: 0-1 variable, such that its value is 1 if option j in gear i is selected, otherwise, it is zero for $j \in J_i$, $i \in I$.

y_g: 0-1 variable, such that its value is 1 if transmission g is selected, otherwise, it is zero for $g \in G$.

The mathematical expression of the model follows.

Objective

Determine the options for each gear to minimize the total deviation

$$\min \sum_{i\in I}\sum_{j\in J_i} w_{ij}x_{ij}. \tag{1}$$

Constraints

$$\sum_{j\in J_i} x_{ij} = 1 \quad \forall\, i \in I \tag{2}$$

$$\sum_{g\in G} y_g = 1 \tag{3}$$

$$\sum_{j\in J_i^g} x_{ij} = y_g \quad \forall\, i \in I, \forall\, g \in G \tag{4}$$

$$u_i \le \sum_{j\in J_i} c_{ij}x_{ij} - \sum_{j\in J_{i+1}} c_{i+1,j}x_{i+1,j} \le U_i \qquad \forall i = 1, 2, \ldots, |I| - 1 \tag{5}$$

$$x_{ij}, y_g \in \{0, 1\} \quad \forall\, i \in I, j \in J_i, g \in G. \tag{6}$$

Constraints (2) force only one option for each gear, and Constraint (3) allows only one transmission. Constraints (4) ensure that the option gear belongs to a set of options related to its transmission. Constraints (5) guarantee a close-ratio transmission in the solution.

Note that for each set G of second transmissions and each set J_i^g of gear options in gear i for transmission g, the calculation of parameter c_{ij} is needed. This preprocessing is required only once for each gear option list.

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Facundo Garcia de la Cuadra, Managing Director, TEAM ASPAR, Pl. Sociedad Musical, 8-3, 46600 Alzira, Spain, writes: "I am writing to inform you that the application described in the paper 'TEAM ASPAR Uses Binary Optimization to Obtain Optimal Gearbox Ratios in Motorcycle Racing' by Amorós and others was in fact implemented at ASPAR TEAM company.

"We are using this model presently, and it has improved our capability of selecting an optimal gearbox configuration for each racing circuit in the world championship motorcycle, because it attends to the preferences of each rider and motorbike. The solution proposed for this methodology allows us to begin the training days with a quasi-optimal configuration gearbox."