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Formula One Technical Regulation
Can Parametric Constraints Offer a Route
to Diversity of Design Solutions?
by
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I hereby declare that, except where specifically indicated, the work submitted herein is my original work ....

Abstract

Formula 1 (F1) is a single seater motor-racing series, widely considered as the most technically advanced and certainly the most viewed. As a result it has attracted increasingly large quantities of investment, and ever more sophisticated technologies. This trajectory has limitations however, and the contradictions this throws up cause concern within F1. The two most fundamental of these are, "How is the technical 'awe' of the sport maintained, whilst still retaining OEM interest?" and "With ever faster development cycles, how are teams prevented from converging on the same solutions so fast such that F1 effectively becomes a spec-car series?" It is in developing a regulatory framework to address these dilemmas that forms the main focus of the project.

In order to define the problem, an initial analysis was carried out into what the desirable outcomes were for the major stakeholders in F1; the fans, the regulator and the competitors. A discussion was also made into the evidence for design convergence in F1. This concluded that F1 is exhibiting an era of convergence, and this is contrary to the desires of the stakeholders of the sport. In addition, more competition, less cost and emphasis on road relevant and green technologies were desired, all without abandoning the 'DNA' of Formula- its 'technical awe'. These conclusions formed the basis of a set of requirements for the proposed regulatory framework.

Three case studies were performed; The America's Cup, Formula SAE and the FIA GT3 World Championship. These were chosen as examples of technological sports where a high degree of design divergence was evident, and a variety of mechanisms which promote design divergence were discussed.

An analysis of the mechanisms for innovation and design divergence which already exist in F1 were also considered. These mechanisms were identified as'The restriction/ radical solution cycle', 'Volatile regulation', 'Ambiguous regulation' and 'Discrete-Parametric' regulation. An extensive data mining exercise was performed to determine the evidence for these mechanisms. There was significant evidence for volatile regulation divergence, transient periods of high diversity followed by convergence were clearly visible in the data. For discrete-parametric regulation (wherein a number of equally performing technologies are permitted), the 1980's provided an excellent example where 3.5L normally aspirated and 1.5L turbo engines were both allowed together. This was also shown to be a particularly competitive period.

Finally, with cost implications seen as the biggest barrier to performance divergence,

methods to remove the desire to spend were considered. A number of proposals were made including performance handicapping, liming the development period through homologation, and preventing future car development by volatile regulation.

With a collection of mechanisms to increase design divergence, control performance divergence and ameliorate the desire for development expenditure two competing proposal regulations were born. The first- 'Open regulation, with Performance Balancing' consisted of a large scale reduction in the geometrically prescriptive regulations followed by performance balancing (addition of weight and power restrictors on the fastest cars) to both remove the desire to spend and keep the sport competitive. Here Power-train regulations were opened up, but it was felt that the performance balancing methods already used by the FIA would be inadequate. An optimisation strategy capable of bringing a grid of 10 representative to cars to within 0.36s was developed. Following a discussion with a former FIA technical delegate, it was felt that performance balancing would damage the 'DNA' of F1 (and therefore did not meet one of the requirements of the regulation).

A second regulation was proposed. 'Discrete Parametric Regulation' (DPR) consisted of the FIA permitting a set of equi-performing technologies. Then, to reduce the desire to spend, the cars are homologated at the beginning of a new season and no further parts are permitted on the car. To prevent re-investment of funds into next year's car; the car regulations are changed at the end of each season ('volatile regulation'). As the first set of permitted technologies, Continuously Variable Transmission (CVT), Energy Recovery System (ERS) or conventional power-train were permitted. These were chosen in order to meet the FIA's green objectives, and the objectives of OEM's to develop road-car relevant technologies. In order to balance the performance of these technologies, the weight limit was adjusted for each solution.

The results of this second proposal were promising. The technologies were equi-performing and this balance was robust to track changes. Further to this, the results predicted a massive increase in the amount of overtaking encountered in a race. Light, conventionally powered cars would 'win' under braking into the corner, and ERS cars would 'win' under acceleration out of the corner. The speed differentials were often > 10kph, which is predicted to be enough to allow an overtake into the corner, followed by a re-overtake out of it Finally a number of the more subtle impacts of DPR were considered.

It was concluded that since the second proposal shows promise in being able to meet all of the requirements, it would be the framework recommended for further investigation.

Contents

1 Introduction

1.1 F1 Today

Formula 1 (F1), arguably the most technically advanced and certainly most watched single-seater racing series has been has been criticised in recent years for not producing a diverse enough array of technologies to keep fans, or manufacturers interested [1] [2] [13] . As the sport grows in wealth and technology progresses, contradictions and tensions are surfacing; with the competing aims of exciting racing, ameliorated development cost, technical 'awe' and design diversity. The sport's governing body, the Federation Internationale De L' Automobile (FIA) has invested considerable resources into finding solutions and intense debate has raged between regulator, fan, competitor and Original Equipment Manufacturer (OEM).

1.2 Scope and Aims

The aim of this work is to first investigate the hypothesis that the F1 spectacle would benefit from a divergence in design concepts, before proposing a regulatory framework which would provide the conditions necessary to encourage this. The scope of the work is to develop such prototype regulations, consider implementation issues, and the wider impacts each would entail. Real-world investigations required for validation of simulation results are discussed but not performed.

Conclusions are supported by extensive race data mining, stakeholder interviews, a lap-time and vehicle dynamics simulator (RaceSim), FIA policy documents and race vehicle design theory.

1.3 Strategy

The approach was to divide the work into four phases:

Phase 1: Defining The Problem

The premise of the work is the hypothesis that a desire exists amongst the stakeholders of Formula One for increased design divergence. This hypothesis is first tested through a literature review and survey data, and other stakeholder desires are then explored.

Phase 2: Research

Examples of mechanisms which promote design divergence are considered, these are demonstrated both within F1 and outside it. By the identification of these mechanisms and the conditions required to facilitate them, proposals can then be designed which reproduce these effects in modern day F1.

Phase 3: Regulation Proposal

Two regulations are proposed based on the research performed.

Phase 4: Regulation Development

These regulations are then developed using the RaceSim lap simulator. The wider implications of each regulation are considered with reference to the additional desires of the stakeholders determined in the problem definition. A proof of concept is performed for each and the detailed requirements for successful real-world implementation discussed.

2 Problem Definition

"As F1 design has become increasingly convergent, the major stakeholders in F1; the FIA, the spectators and the teams, desire more design divergence in the sport"

Does evidence exist to support this statement?

2.1 F1 Design has Become Increasingly Convergent

By a subjective analysis of appearance the F1 grid showcases a much narrower array of solutions compared to other periods in the sport's history.

Figure 1: Comparison of F1 grids from 1970's and 2000's

To quantify this convergence, the development of around 70 design parameters over 50 years were collated from three[1] on-line sources [4] [6] [5]. Despite requests made to the sources access to the raw data files was denied. Instead, a series of Visual Basic (VB) scripts were written to sort through those website's web-pages and extract and process the data from the HTML files. Four examples are shown below with convergence parameters λ defined below, where $\lambda > 1$ implies design convergence.

$$lambda_m = \frac{\max_{1970} - \min_{1970}}{\max_{2000} - \min_{2000}} \quad \text{and} \quad \lambda_\sigma = \frac{\sigma_{1970}}{\sigma_{2000}}$$

Quantity	λ_m	λ_σ
Number of Engine Cylinders	∞	∞
Rear Track †	2.5	7.2
Front Track	10	11
Wheelbase	4.8	5.4

Table 1: Quantitative Design convergence in F1 between 1970 and 2000

† The track is the width' measured between the outside rim of the two front/ rear wheels.

[1]Data was patchy, it was therefore necessary to bring multiple sources together to fully map the design space.

This analysis (including the other design variables) suggested a strong driving force for design convergence between 1970 and 2000. To support these conclusions a literature review performed, which showed other work in this area had conclude likewise [11] [12]. Some technical commentators even compare the look of modern Formula One to a spec-car series[2] [13].

2.1.1 Why do Designs Converge in F1?

A key facilitator for design convergence in F1 is the regulatory framework the sport endures, characterised by heavy emphasis on *geometric constraints*. Geometric constraints are those regulations which put a direct constraint on the final design of a system. This contrasts to a *parametric* constraint where a performance parameter (power, downforce, etc.) is limited without prescribing the geometry. Examples taken from the 2012 FIA technical regulations are shown below [14]:

On bodywork *...there must be no bodywork in the area formed by two vertical lines, one 325mm behind the front wheel centre line, one 450mm ahead of the front wheel centre line, one diagonal line intersecting the vertical lines at 100mm and 200mm above the reference plane respectively....* ***On engines*** *...8 cylinders arranged in a 90º "V" configuration and the normal section of each cylinder must be circular.*

To interpret this more formally the concept of a *performance surface* is introduced. The performance surface is an n-dimensional manifold generated when some performance metric (such as laptime) is considered a function of the car parameters. The surface consists of peaks and troughs corresponding to high performance and low performance and the bounds on the feasible region are defined by the regulator. Geometric constraints limit the size of the feasible surface area, and hence the number of available performance optima. The corollary of this is then clear; race car designers, given appropriate time allowance, converge on the same solutions. Based on this evidence it is logical to pose the questions

- Does an alternative to regulation by geometric constraints exist?
- Are there other environmental factors, other than regulation, which affect design divergence?
- What mechanisms already exist in F1 to allow teams to diversify?

These questions are addressed in the following sections.

2.2 F1's Stakeholders Desire Design Divergence

2.2.1 The Spectator

The concept of 'design divergence' is relatively abstract to the passive spectator and as a result no reliable data exist on the explicit desires of the spectator in this context [7]. Thus

[2] A spec-car series is one where the design of every car is identical, by regulation.

the marketing concept of an *implied need* was employed. An implied need is one that is not explicitly stated by the customer but can be deduced from their responses to defining the problem[3]. A 2005 FIA study [3] investigated the desires of over 93,000 fans making it the largest motorsport poll ever conducted. Using these data, an *implied desire* was deduced from answers to much less abstract questions. This implied desire was quantified using the method below.

Statistic	*Implied Desire*	*Correlation*
94% Want more overtaking	Increased divergence	Strong
74% Want more emphasis on driver skill	Increased convergence	Moderate [4]
88% Say showcasing the skills is the most essential aspect of Formula One	Increased convergence	Moderate
80% Agree advanced technology sets F1 apart from other motor sports	Increased divergence	Moderate
64% Look forward to the technical innovations each season	Increased divergence	Strong
74% Want more emphasis on driver skill and less on driver aids	Neutral	N.A

Table 2: Tabulated summary of the data from the FIA study and it's relevance to design divergency [3]

Each statistic (the % vote) is weighted by a factor representing how correlated (or relevant) the opinion is to design divergence; Strong (3), Moderate (2), Weak (1), and negated for a desired *convergence*. Therefore $D_{fan} > 0$ implies overall desired divergence, $D_{fan} < 0$ convergence.

$$D_{fan} = 0.94 \times 3 + 0.74 \times -2 + 0.88 \times -2 + 0.8 \times 2 + 0.64 \times 3 + 0.74 \times 0 = 3.1$$

Thus the survey data suggest a desire for design divergence amongst fans in general. A review of commentary from the technical media, where design divergence was this time *explicitly* discussed corroborated this view, for instance [1] [2] [13]. No evidence of contrary opinion could be found. Further supporting evidence emerges when considering a counter-factual example of IndyCar. In the mid-1990's in response to spectator concerns around the lack of competition in the sport, and with no *explicit* public demand for design divergence IndyCar moved towards effectively becoming a spec series. As a result (and other contributing factors) IndyCar viewing figures slumped, and the sport received intense technical criticism from the media and fans [8] [7].

It is therefore concluded *the F1 fan desires increased design divergence, but is cautious of the impact on other aspects of racing such as overtaking or driver skill.*

[3] In other words, the customer wants it, but doesn't realise.

2.2.2 The Regulator

The FIA has not explicitly stated a position on the concept of design diversity [7]. However, the FIA contractually requires for each team to behave as a 'constructor' and by implication produce independently designed cars. The FIA also has a clear objective of increasing the sport's fan base, with the particular aim of increasing revenues in order to make the sport more financially sustainable. To that end the FIA also has a strong reluctance to engage in any activity that would increase costs for the sport's participants. The FIA sees itself as having a role in protecting against changes which would undermine the legitimacy of the sport itself, F1's 'DNA': *"Formula One must retain its technical 'awe"'*[33]. The FIA also wishes to protect the sport against accusations of glorifying excess and alienation from an increasingly environmentally concerned public, and hence move the sport in an environmentally sustainable direction [10]. Above all however, it is the FIA which is responsible for the safety of the sport.

2.2.3 Teams and OEM's

The principle concern of the competitors is the economic sustainability of the sport [12]. With engineering budget's increasingly squeezed, the manufacturers (generally) desire both a reduction in the overall cost of competing, but also of ameliorating costs through R&D development shared between road-car and racing-car. This can be achieved when F1 innovates along the lines of *road relevant* technologies. These issues have posed major political problems in recent years, three major road-car manufacturers (BMW, Toyota, Honda) all left the sport in recent years on a cost vs benefit analysis [9].

3 Requirements of the Proposed Framework

Based on the research discussed thus far, in order that a pro-design divergence framework is to be accepted by the major stakeholders in F1 a number of additional criteria should be met. It is against these criteria that the likely success of proposed regulations will be judged. The framework should:

1. Promote design divergence (fan desire)
2. Increase the propensity for overtaking, avoid single team dominance, and emphasise driver skill- increase the sports 'competitiveness' (fan desire)
3. Create an environment where energy efficient technologies can be explored (FIA desire)
4. Provide an environment where road relevant technologies can be explored (OEM desire)
5. Not act to increase the financial expense required to remain competitive (team/ FIA desire)
6. Maintain the 'DNA' of F1 (fan/team/FIA desire)

4 What Environmental Factors Affect Design Divergence?

Three case studies were performed to provide answers to this question, chosen as prime examples of technically diverse sports. The factors that enable design divergence are tested against the additional requirements set out above. Consideration is also made to how the sporting environments differ to F1.

4.1 The America's Cup

The America's Cup is a one-on-one yachting trophy won by contesting a match of around five legs. There are many parallels with the technological development in this competition and F1, with both viewing themselves as the pinnacle of their respective sports. Developing the Yachts entering the America's Cup for instance, can reach upwards of $50M [15]. The technical regulations of the America's Cup tend to be far less prescriptive than that those in F1. Although some geometric regulation of certain parts of the yacht are constrained, there are few major constraints, a minimum weight, a hull length, and the number of sails permitted [16].

Even with the relatively small number of systems to develop, yacht makers commonly find very different design solutions. The example below of the 2010 America's Cup where both catermeran and trimeran designs were entered.

Figure 2: The two competing yacht designs in the 2010 America's Cup

Five factors are proposed which give rise to this degree of design divergence;

1. *Limited technological regulation.* The America's Cup is much more lightly regulated that F1.
2. *Unpredictable externalities.* Weather is one example, the decision to run trimeran (heavy wind optimal) or catermeran (light wind optimal) must be made at the design stage well before the conditions are known. In F1, cars are routinely adjusted (ie. optimised) to the prevailing weather conditions in almost real-time.
3. *Human Behaviour.* Design ethos in the America's Cup strongly flows from the direction of the (typically billionaire) team owner, differing sharply from the data driven decisions based on the simulate/ test cycle used in all modern F1 teams.

4. *Competition Format.* The competition consists of one head-to-head match (albeit over a number of legs), meaning the calculus of winning is different from a season of 18 events all in different venues, with 24 cars contesting 60 or so lap races. Designers are more likely to experiment with a radical concept in a one-shot win/loose scenario, particularly if they feel they are the underdog. In a competition over much longer time periods, the performance (dis)benefits of a risky design are averaged out, promoting more conservative approaches.

4.2 Formula SAE

Formula SAE, is a collegiate engineering design competition created by the Society of Automotive Engineers (SAE), allowing students to design, build and race seater race cars. The competition uses a points system, awarded for design knowledge, track performance etc. The regulatory framework is relaxed compared to other forms of motorsport, focused on creating a safe learning environment. Despite long-term stability of the regulations, there is little apparent design convergence. Vastly different power-trains; single cylinder, 4 cylinder and electric all race competitively together, and some teams operate enormous wing assemblies whilst others do not use any aerodynamic devices at all.

A paper written in 2005 made conclusions to the most common hypotheses as to why a formula with rule stability for such a long period has not seen design convergence [18]. The underlying cause was the 'ameturness' of the teams, leading to non-optimal design solutions, slow convergence and opinion (rather than data)-led design decisions. The technical awe, integral to the 'DNA' of F1 is not compatible with such divergence mechanisms.

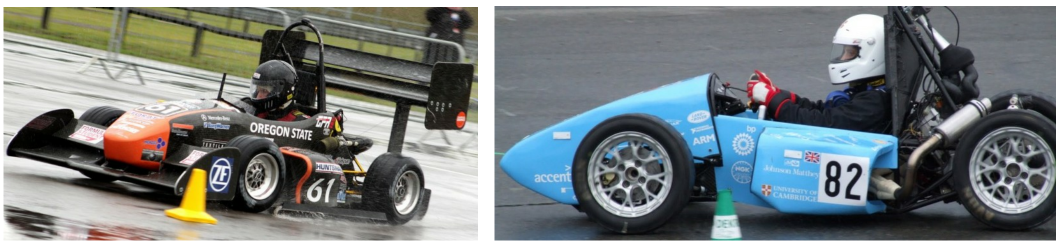


Figure 3: Typical example of the vastly different approaches to aerodynamics in FSAE

4.3 The FIA GT3 Championship

4.3.1 GT3 Showcases a Diverse Range of Technologies

GT3 is a sports car championship, competed by amateur drivers supported by small teams. The cars are supplied by road car OEM's, originally selling them for profit before the focusing on marketing technology to spectators [19]. In GT3 racing it is required that all cars racing must be road models.

Supported by relaxed technical regulation, the design space explored in GT3 is large, because of the requirement to run road car models. Examples of this are; a range of masses from 1100-1400 kg, engine powers from 430-560 Hp, and wheelbases from 2400-2700 mm [21]. This contrasts F1 with homogeneous car weight and wheelbase lengths, and a power range of $\approx$ 50hp.

4.3.2 GT3 Racing is a Competitive Formula

In order to test the GT3 regulation framework against requirement 2 (competitiveness), race data were taken from 5 years of F1 and GT3 racing and compared. GT1, which possesses a similar regulatory framework and competition format, was also included to improve the validity of the analysis. The competitiveness metric used here is the percentage of competition entrants who won at least one race in a given season. The number of races is also shown, the expected result of increasing the length of the season would be an increase in the number of individual race winners [5].

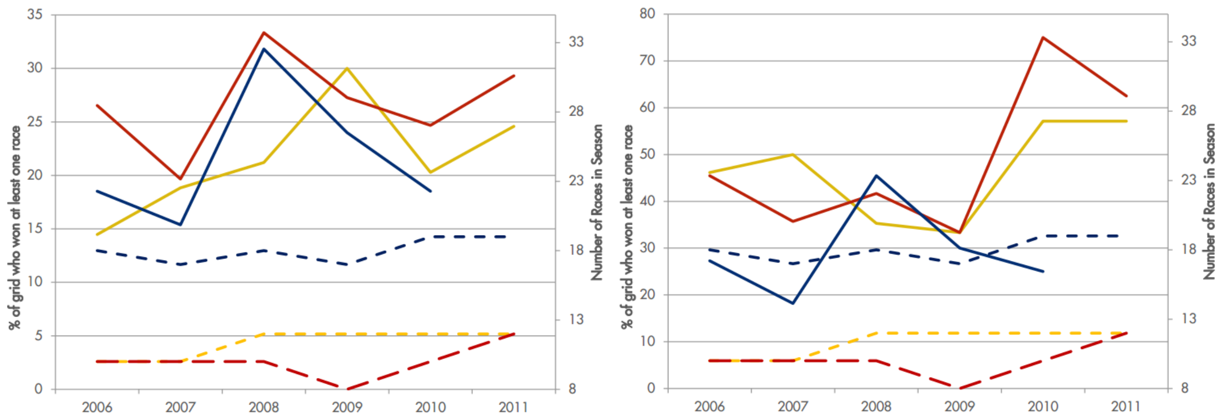


Figure 4: Proportion of entrants who win at least one race. Right: Teams, Left: Drivers. Red: GT1, Yellow: GT3, Blue: F1. Dashed: No. Races, Solid: Proportion of winners.

With a larger percentage of entrants winning races in all but one year even with less races per season it is concluded that GT racing exhibits larger competitiveness (requirement 2) *despite* the large diversity of car technology.

[5]The precise relationship between number of races and expected number of race winners cannot be calculated without knowledge of the probability an individual driver will win a race however.

Championship	*Podium Finishers*
GT1	49%
GT3	43%
F1	29%

Table 3: Percentage of championship drivers who scored podium finishers in 2010

4.3.3 GT3 is made Competitive by Performance Normalisation

To maintain this competitiveness the FIA adopt two strategies to limit the performance differentials between cars over the season, which are collectively referred to in this work as performance normalisation:

Performance Balancing. Each car model's performance is balanced *pre-season*, using complementary track and simulation data at FIA organised test events. The modus operandi is to normalise the car's top speeds with the restrictor and then normalise lap times with additional ballast.

Success Handicapping. Success handicaps occur mid season, penalising well performing teams. Ballast is added or taken away from the cars for a race dependent on where they finished in the previous race (1st: +20kg, 2nd:+15kg...). In 2011 this was altered to a time penalty, served during the pit-stop.

In order to determine the effectiveness of the performance normalisation techniques in GT3 on promoting competitiveness, a data mining exercise was performed computing race and qualifying data from 6 seasons (2006-2011). To investigate the effect of additional ballast (through success handicapping) on performance a 'base line' position, the average finishing position with zero ballast, was calculate for each team for race and qualifying separately. The correlation in the difference between base-line and finishing position when carrying ballast (5kg to 50kg in increments of 5kg) was sought, to prove weight handicapping was adequately reducing performance.

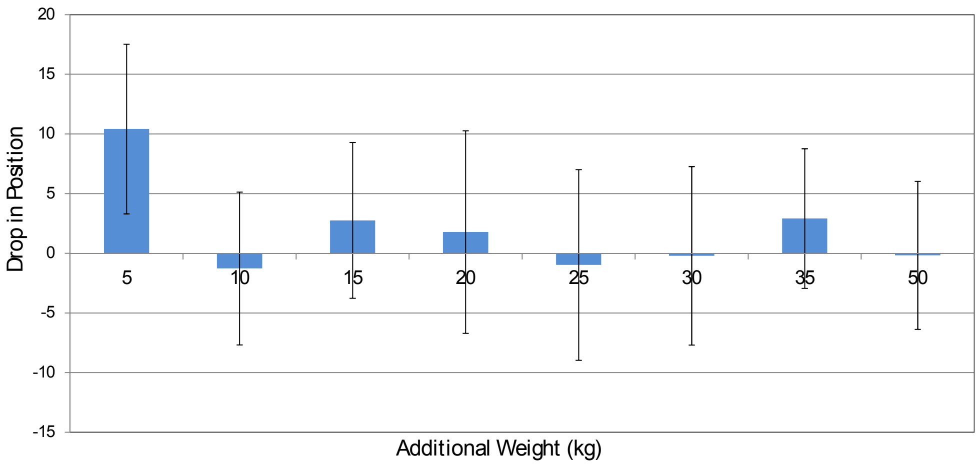


Figure 5: Average Change in position following a ballast success handicap

A statistically significant correlation is seen above between weight handicapping and a performance drop, but the signal-to-noise ratio was too small to determine a relationship between the *amount* of ballast and the *amount* of performance loss. The data also highlighted that there was an uneven handicapping effect, lighter cars have a larger (10-15%) ballast handicap as a proportion of their starting weight.

There was still evidence for an un-eveness of handicap after correcting for this, suggesting second order effects (ie. some cars are less sensitive to ballast addition), tyre degradation is likely to be the dominant 2nd order factor here. This 'unfairness' would damage F1's 'DNA' (requirement 6), so would not be pursued.

4.3.4 Performance Normalisation Does Not Kill the 'DNA' of GT3

In order to determine the impact on the 'DNA' of *GT3* (requirement 6 for F1) in introducing performance normalisation a conversation was opened with the stakeholders in the sport. Following a conversation with the GT3 FIA technical delegate Peter Wright, these were identified as;

1. *The OEM's.*
2. *The Promoter.* Stephane Ratel created the series, and profits from the entry fees he receives from teams and drivers.
3. *The Drivers.* The drivers are typically funded by their own sponsors, particularly relevant for the younger drivers who enter GT3 in order to gain experience for higher forms of racing.
4. *The Teams.* The teams must buy the GT cars from the manufacturers, and are free to set up the cars themselves, but do not undertake any design work themselves.
5. *The FIA.* The FIA governs the sport. Typically racing series apply for governance from the FIA [23] who then administer this side of the sport. The FIA administers all performance balancing an success handicapping in GT3.

In order to determine the views of the various stakeholders a number of teams were approached with a list of questions, two responded. The promoter was contacted but did not respond, and a phone discussion with the regulator (Peter Wright) was conducted. The conclusions are listed below;

- Manufacturers involve themselves in sports car racing to promote the racing or sporty side of the brand. In sports car racing, the cars look similar to the road cars and hence an easy association is made in the customer's mind.
- Performance normalisation is seen as necessary to allow a competition to exist with such a wide array of design concepts. Manufacturers see a small negative aspect, spectators often mistake a handicapped effects as product failures.

- Finding the new optima through setup changes, after a handicap is applied not seen as a difficult or time consuming task.
- Under-performing to avoid handicaps in order to win the championship is not seen as a common occurrence, the marketing cost of deliberately under-performing is too high (as is the team desire to win).
- The performance balancing is considered successful if the spread of car performances is <0.5sec (lap time) <5kph (maximum velocity), before driver effects.

In summary, within GT3, stakeholders see the performance balancing as a necessity and although it has some negative implications, these are do not pose any major questions to the legitimacy of the sport.

5 Design Divergence Inside Formula 1

5.1 Proposed Mechanisms of Innovation

The second half of the research phase was to determine what mechanisms of innovation (with reference to the regulations) already exist in F1. By utilising these mechanisms in the proposal regulations, innovation (and therefore design divergence) can be promoted.

5.1.1 The Restriction/ Radical Solution Cycle

The effect of the size of the design space on radical innovation has been the subject of much academic research, in a wider engineering context. It is argued [32] that mechanisms exist such that innovation can occur both despite and *because of* resource constraints. In the latter case, designers are forced to adopt approaches previously thought undesirable, and results previously unpredicted are found.

Proposed during the World Motorsport Symposium (WMS) in January 2012 [31], the restriction/ radical solution cycle (illustrated below) demonstrates how severely restrictive regulations can result in designers resorting to extreme solutions in order to find a performance advantage.

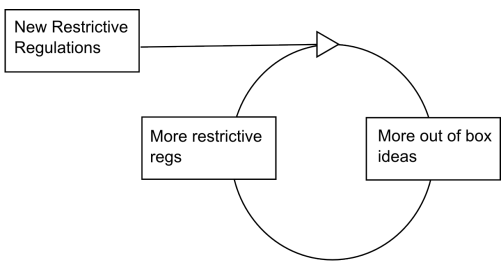


Figure 6: The innovation regulation cycle

Box 1: W-Duct Case Study At the end of the 2010 season a new aerodynamic technology for that season *the F-Duct* was banned. The device consisted of an internal series of ducts which, when activated by the driver, fed air onto the rear wing, stalling the airflow and thus reducing drag. As a highly expensive technology the teams and FIA alike were determined to prevent the technology from being permitted in future seasons, and effort was spent devising a set of severly restrictive regulations with this purpose. In 2012 however, Mercedes F1 introduced an extreme rethink of the f-duct concept ('out-of-the-box thinking), this time ducting air from a flap in the rear wing in order to stall front wing, a technically much more challenging achievement, and yielding a signficant performance advantage.

5.1.2 Volatile Regulations

A change in one area of the car enforced by regulation, often pushes another coupled system out of its performance optimum, indirectly creating scope for new innovation and design divergence. In motorsport there is a high propensity for this indirect divergence to occur where small performance margins and complicated interconnected systems exist.

5.1.3 Parallel 'Discrete-parametric' Regulation

The regulator permits certain technology 'bundles', in parallel, and with similar performances. In the 1977 technical regulations, two equi-performing power-train solutions were permitted; either 3.5L normally aspirated or 1.5L turbo. This is an example of *discrete-parametric* regulation.

Box 2: Parametric Regulation In the geometric regulatory framework (2.1.1), the regulator achieves his or her objective by defining the feasible region on the *design* surface. In parametric regulation, the regulator acts to constrain designers to a particular *contour* on the *performance* surface. The entire design space is left open, but the performance of the particular system is defined. Thus the design space is not only bigger, but in ideality the number of performance optima is zero and hence the incentive for design convergence (on purely performance grounds) is removed. In reality however, the contours are not well defined (either they differ track to track, car to car, or just not well understood) so even the best designed regulations will have 'fuzzy' contours, potentially leading to optima appearing, and hence design convergence. If the number of solutions permitted on this equi-performing contour is limited, this is defined as 'discrete-parametric' regulation, the turbocharge regulations are an example.

5.2 Innovation Results in Ephemeral Design Diversity

It was asserted that innovation is a route to design divergence, but how long does the design divergence last? New innovation is cheaper (and safer) to achieve by copying the work of another team rather than introduce a new concept. Preventing such 'espionage' is almost impossible with the series broadcast live on TV, although the main factor is the mobile engineering labour force. The speed of this convergence can be analysed however, and choosing a framework which maximises the convergence time constant made part of the regulation development aims. This time constant is highly dependent on the nature of the innovation itself; what are the system level impacts of introducing a particular innovation? It is not obvious that there should be any relationship between the speed of design convergence, and the mechanism in which the innovation occurred.

The concept of a *time constant* is introduced. This is defined by the author as the time before 63% of the teams have converged on a similar solution. This characterises the rate of convergence discussed in the data analysis, and the relationship follows a characteristic shown below

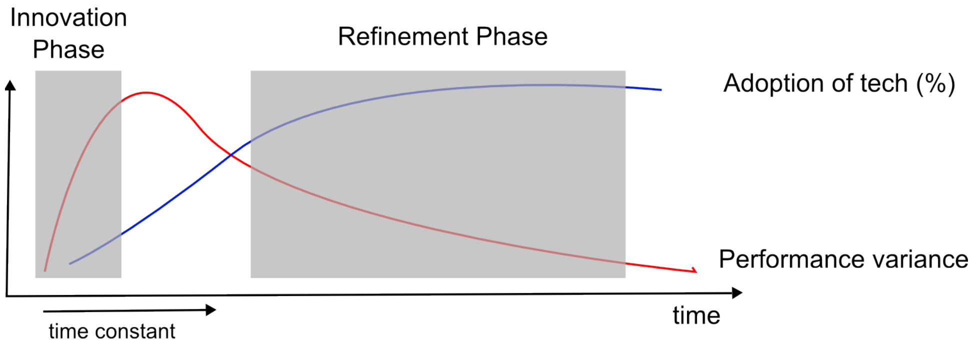


Figure 7: Design and performance development following a new innovation

The form of the innovation causing divergence affects the properties of this characteristic curve. Innovations which are difficult for other participants to discover or significantly impact the design at a systems level cause a larger lag between first adoption and follower adoption. Innovations which require a lot of development act to increase the time constant of design convergence. Some examples were calculated overleaf

Innovation	*Introduction*	*Notes*	τ
Double diffuser	2009 by Brawn, Williams, Toyota	Improves downforce by increasing the expansion volume at the rear of the diffuser. Easy to spot, not difficult to alter an existing design.	9 weeks
F-Duct	2010 by McLaren	Reduces drag by stalling the rear wing. Very visible, difficult to implement.	14 weeks
W-Duct	2012 by Mercedes	Reduces drag by stalling the front wing. Very difficult to work into a new design	Unknown, > 12 weeks

Table 4: Convergence time-constants for selected innovations

5.3 Innovation Cause Performance Divergence

Beyond investigating how innovation affects the design diversity, consideration is also made into how it affects other desirables in F1. In particular the concept of *competitiveness* is considered (requirement 2). It is the quantity *performance divergence* which alters the competitiveness of the grid. Two forms of performance divergence are defined:

- *Good-type performance divergence.* Performance differentials in the midfield are large enough to allow overtaking but are inconsistent, preventing predictable results.
- *Bad-type performance divergence.* The differential between the top car and the rest increases, resulting in single team dominance.

5.4 Innovation Mechanisms in F1: The Evidence

5.4.1 Investigation Outline

The evidence for the innovation mechanisms proposed above is now considered. An extensive data mining exercise using data from the FORIX web resource was performed [6]. A number of questions were posed regarding both the *design* divergence and the *performance divergence* :

- In the long-run (inter-season) track lap time data, when were performances most diverse?
- What regulator framework did this correspond to? Can a causal link be concluded?,
- Considering long-run *design* data, when and why do their designs diverge?
- How is the competitiveness affected by the amount of design divergence in that season?

The race data are extremely noisy, caused by the multitude of random events that can occur within the race. For this reason the approach was taken in considering the patchwork of evidence from different data sets and different forms of analysis in order to support conclusions.

Data	*Analyses used*
Qualifying (top 9)	•Time delta from pole: Coefficient of Variation (CoV)*. Performance variation, normalised for different tracks and conditions. •Time delta from pole: Average Delta. Direct measure of performance divergence, but not normalised for different tracks. •Time delta from pole: Standard Deviation. Non-normalised form of the CoV.
Laptime	•CoV of lap times (normalised). Measure of absolute performance spread. •Quartile Coefficient of Dispersion (QCoD). Removes upper/lower ends of sample. Better comparison of 'midfield' spread. •Average deviation. Weighted less heavily to extreme ends of the sample compared to CoV, so a more balanced view of the spread.
Speed trap	As above; CoV, QCoD, Normalised Average Deviation
Car design	Parameters analysed; Car length, Wheelbase, Front track, Rear track, Fuel Capacity. Raw data investigated graphically, and CoV calculated for each parameter.
DNF's**	Total in number season per driver per race

Table 5: Summary of analyses used in F1 data mining

*$CoV = \sigma/\mu$ ** Did Not Finish

5.4.2 Proposed Mechanisms of Innovation Past F1 Regulations Impacted on Performance Divergence?

In order to support the development of the proposed regulations to meet requirement 2, past experience of regulation impact on competitiveness was investigated.

Long-run (inter-season) race and qualifying data, for individual circuits were analysed as described above. Two examples are shown overleaf.

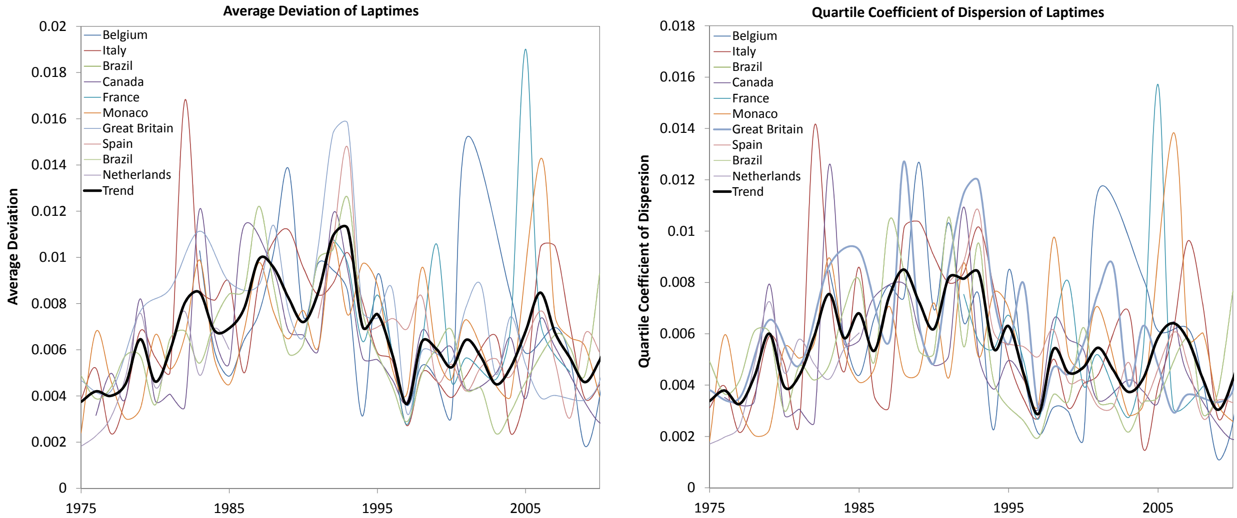


Figure 8: Measures of lap-time spread for different tracks over 40 years showing increased performance divergence during 1980's

Considering these data, and the corresponding qualifying and speed trap data with the analyses outlined in 5.4.1 (which showed similar patterns) a consistent trend emerges: a rise in the divergence of performance in the 1980's, followed by a drop off into the 1990's and 2000's, returning to a similar level seen in the 1970's.

In fig. 6. the performance divergence signal is seen in the average deviation data, but is maintained after the top and bottom performing cars are removed (ie. in the QCoD analysis). This suggests *good-type* performance divergence, the performance differentials exist in the mid-field, and the season is not subjected to single-team dominance. To investigate this further a competitiveness analysis is then performed.

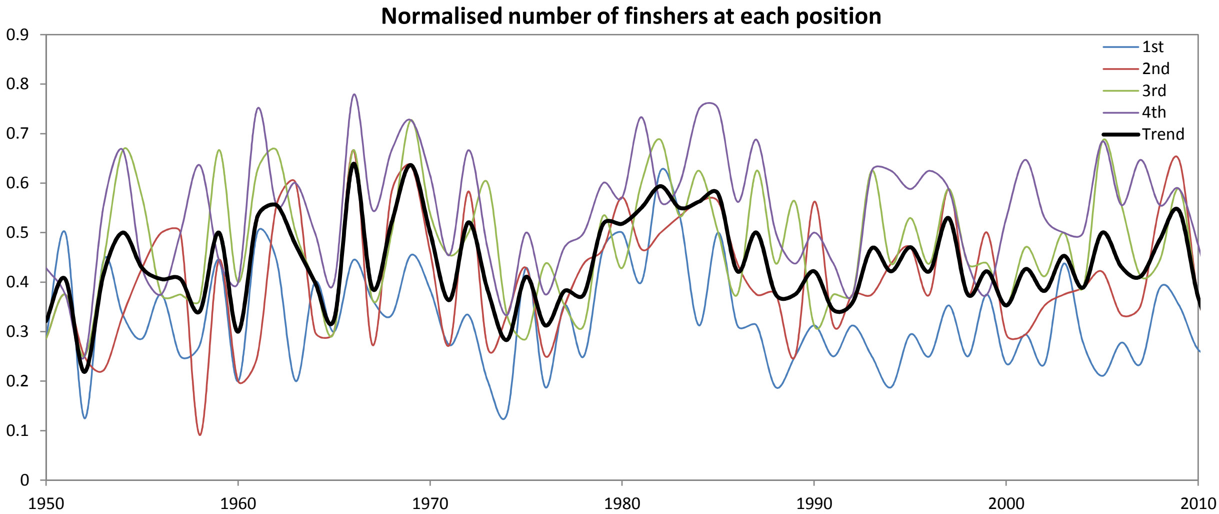


Figure 9: Number of different drivers finishing in each position.

The competitiveness metric used here is the number of *different* race finishers in each position (1,2,3,4) over the season, normalised to the number of races and entrants in the season. The data in fig. 7. suggest F1 in the 1980's is moderately *more* competitive than the periods immediately before or after it. The performance divergence described here coincides with the turbo era solutions discussed in 5.1.3, the effect of discrete parametric regulation is to compete turbo and non-turbo cars against one another creating a much wider variety in race results.

5.4.3 Restrictive Regulations Improve Reliability

An investigation of F1 reliability data from 1950-2011 showed a drop in the number of retirements from 50% (±10%) in the mid-1980's to 25% (±5%) between 2007 and 2011 (when engine development was restricted). It is proposed that by restricting innovation, development focuses on making what already exists more reliable. This may have a negative effect on the entertainment of the race as one element of suspense is removed (ie. *'will driver X make it to the end of the race?'*).

5.4.4 How Have Past F1 Regulations Affected Design Divergence?

In order to confirm the existence of innovation and divergence mechanisms proposed, a correlation between the divergence in certain car parameters (weight, wheelbase, front/ rear track and fuel capacity [6]) and the regulations implemented by the FIA was sought. Data from 1970-2010 were used in this investigation. Only weight and rear track length are included in this report, analysis of the other parameters drew similar conclusions and evidence of this can be found in the electronic log.

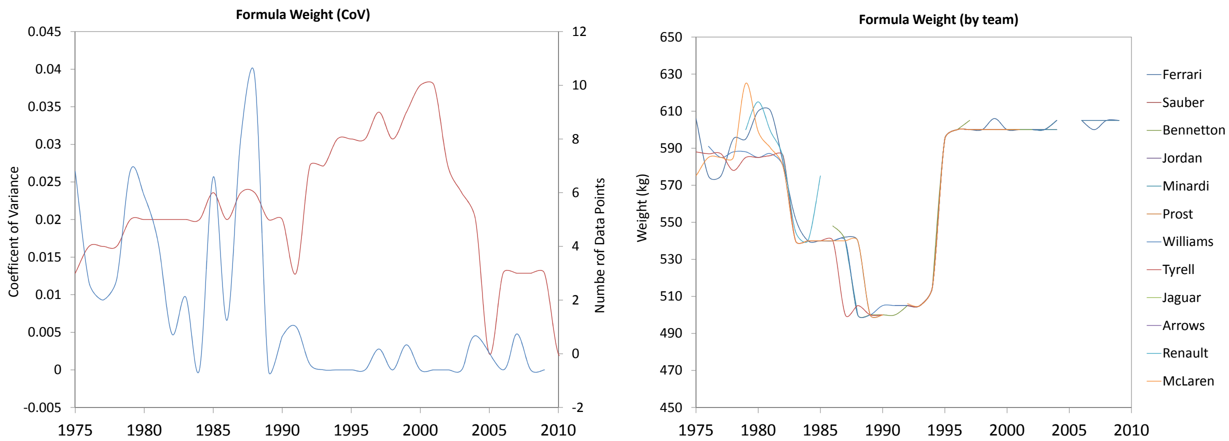


Figure 10: Divergence in car weights for 11 teams over 40 seasons. Left: Coefficient of variance (blue) and number of data points (red). Right: Absolute car mass by team. 1980/5/7 show 'spikes' in divergence.

A trend in the variance of car weights is apparent by considering the following regulation changes-

- 1980- Min. weight restricted 575kg
- 1985- Mandatory crash tests introduced

[6]These parameters were chosen as the largest quantity of data was readily available

- 1987- Min. weight restricted to 500kg
- 1995- Min. weight restricted to 600kg now inc. driver

Where being competitive following a new regulation *poses a challenge*, a spike in the divergence of solutions is observed in fig 8. In 1980 and 1987 a drop in the weight restriction caused a ‘scramble’ downwards over the period of about 3 seasons, by which point the teams converge on the new lower weight limit. Similarly in 1985 a spike in diversity is observed, as teams struggle to produce a strong enough chassis to meet the regulations, and still minimize weight. The regulations which make it *easier* to maintain performance (e.g. when the minimum weight is *increased*), unsurprisingly no corresponding jump in divergence is observed, the teams converge to the new feasible optimum immediately. Similar conclusions were drawn when considering the rear track legnth data.

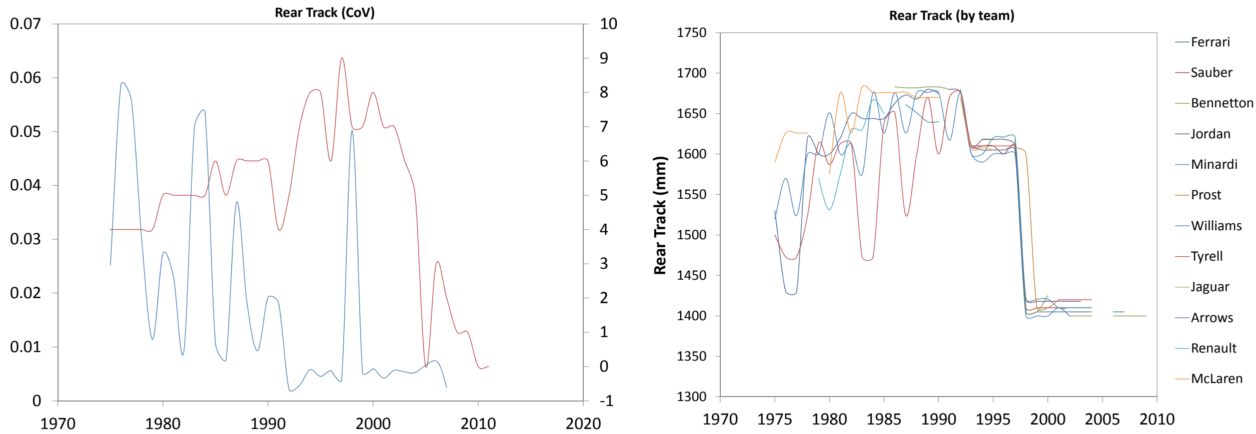


Figure 11: Divergence in rear track lengths for 11 teams over 40 seasons. Left: Coefficient of variance (blue) and number of data points (red). Right: Rear track lengths by team

For this, the set of relevant regulatory changes are

- 1976- change to pedal box safety structure regulation, crash structures around pedals introduced.
- 1983- Ground effect banned
- 1993- Complete wheel width reduced (18” to 15”) implying track width constraint change[7].
- 1998- Allowed track width reduced

Pro-diversity safety regulation in 1976 and 1983 are apparent, and anti-diversivty regulations in 1993. In 1976 the pedal box regulations effect the front geometry, and to compensate the rear geometry (and therefore track) are redesigned. ‘Scrambling’ to find the optimum, a divergency is seen, this is an *indirect* divergence mechanism since the regulation affected the front of the car.

[7]Since track width is measured between the outside plane of each wheel rim.

5.4.5 The Evidence for Divergent Mechanisms in F1: Conclusions

In the design divergence investigations it was observed that 'regulation step change' is a strong mechanism for design divergence. It is characterised by transient diversity as teams scramble to create a competitive car in the new design space permitted, before convergence to the optimal solution. Those regulation changes where the new optimum is easy to attain, show no signs of improving design divergence. Three variants of design transition caused by the regulation step changes are observed;

1. Convergent transition: An FIA imposed constraint means during the transition all cars fit exactly to the regulation, e.g. weight limit.
2. Direct divergent transition: Either a technology or regulation change incentivises the designer to explore new areas, e.g. Kinetic Energy Recovery System (KERS).
3. Indirect divergent transition: A constraint in one area of the car means that when other parameters are changed to compensate, the choices lead to design divergency. e.g. Rear track

The 'Discrete-Parametric' regulation in the 1980's was shown to improve competitiveness signficantly, but the design divergence did not show up in the parameters shown here (as it was a power-train regulation). Likewise with the restrictive/ radical solution cycle.

Performance divergence was investigated in response to the desire of the spectators for increased competitiveness (requirement 2). The investigations showed an increase in the competitiveness of the championship during the 1980s. This period coincided with the discrete parametric regulation: large naturally aspirated engines to race against smaller, turbocharged engines of similar performance. These regulations therefore brought about both design divergence and competitive, exciting racing.

6 Financial Implications

6.1 Design Divergence Costs More

The principle behind the inclusion of cost amelioration as part of the specification (5) for a successful, pro-design divergence regulation, is that increasing the design space *per se* necessarily brings higher costs in order to stay competitive. This is self-evident, greater expense is accrued if a competitor must explore a larger array of design trajectories to find the competitive optimum. The objective therefore is to consider how the regulation can be formed in such a way that this effect is balanced by creating a cost efficient environment in which to innovate.

6.2 Removing the Desire to Spend

In order to address these issues, and reflect the concerns of the teams the FIA set up the Cost Reduction Working Group (CRWG). A paper produced on this subject [33] drew conclusions on the data on this subject and made proposals with the aim of improving the commercial outlook for the teams, whilst preserving the 'DNA' of the sport.

The report proposed 3 solutions to remove the desire to spend;

1. Making a random element play a dominant role. Points for qualifying or 'reverse grid' sprint races (similar to GP2) were suggested as methods to achieve this.
2. Making driver role more significant. Encouraging nose-to-tail racing was proposed.
3. Performance handicapping.

A final two proposals to remove the desire to spend are proposed by the author;

4. Limit the time available to spend. As an indirect method of preventing excessive spending by placing a cap, limiting the amount of time team's have to develop the car would limit the amount of cash the teams are able to spend. The method is based on the assumption that the *rate of spend* is a limited quantity, and teams find it difficult to alter this in response to regulation changes (ie. working around the 'spirit' of the regulation, and spending the same amount despite the time cap[8]). The spend differential between teams can therefore be managed by altering the amount of development time allowed, given that team's have intrinsically different maximum rates of cash spend.
5. Homologation coupled with volatile regulation. By enforcing a periodic homologation of the whole car (or large parts of it), there is no incentive to further develop that year's car. An incentive to switch development to next year's car would then exist, but with volatile regulation this is attenuated as teams are unable to predict how the regulated specifications of next year's car. This mechanism can be used as the limit on time-to-spend in the application of the method above.

7 Proposed Regulations

7.1 Method

The work thus far laid out a number of routes to successfully meeting three of the regulation requirements; increased design divergence, increased competitiveness, reduced cost. Examples of the mechanisms required to achieved this exist both inside and outside F1, and the evidence for their existence has been discussed. The work now focuses on how these concepts can be combined to generate proposal regulations to meet the specification. Two such proposals are made.

7.2 Proposal 1: Open Regulations, Performance Balancing

Inspired by the example of GT3, the technical restriction is greatly relaxed, allowing a large number of competing designs to enter and performance balancing techniques are then used

[8]There is feeling within F1 that teams engage in practices not in keeping with the spirit of the current direct budget caps- because they are able to.

to remove the desire to spend. The desire to replicate a competitors designs is also reduced since gaining a performance benefit through 'espionage' will simply result in an additional handicap. The focus therefore switches to the performance of the driver rather than the car, and the manufacturer focuses on producing innovative technologies as part of winning the *brand* competition, as is the incentive for teams to enter the GT championship.

7.3 Proposal 2: Discrete Parametric Regulation, Time Constrained Cash Spend

A variant of the success of the regulatory approach of the 1980s is proposed. A number of different concepts are permitted by the FIA at the end of a particular season. These concepts should have equal performance characteristics, promoting diversity in the adoption. To prevent teams from trying to investigate every possible solution and picking the optimum, the cars are homologated at a certain point in the year (e.g. the start of the season). This prevents excessive expenditure, and providing the development time is made shorter than the time constant of convergence, it could also create a very diverse field. There is no incentive to invest in next year's car, the new regulations at the end of the season are sufficiently new to make any work obsolete. The 'allowed concepts' can be chosen to suit the needs of the stakeholders in the sport, ie. meet requirements 3,4,6.

8 Regulation Development: Proposal 1

8.1 Process

A proof of concept of the proposal regulation using a combination of open regulation and performance balancing was performed, implemented in four stages

1. Defining the scope of the 'openness'. Defining how the current regulations change in order to permit (and encourage) a greater diversity of design. Consideration is given to the requirements of the stakeholders in selecting the regulations areas 'freed' up.
2. Investigating FIA-type performance balancing. Methodology already exists to perform performance balancing, as used by the FIA in GT3. This is investigated as a 'control' method, but this balance is too 'rough' to be used in F1.
3. Developing new performance balancing techniques. In order to achieve a much finer balance in performance, new techniques are then developed and compared to the FIA control.
4. Discussion of outcomes. Following the results of the performance balancing investigations, conclusions are drawn as to the viability of its introduction into F1.

The RaceSim simulator package is used to simulate and investigate these effects. The algorithm RaceSim uses is discussed in the appendix.

8.2 Opening Pandora's Box

In order to determine the focus, stakeholder desires are considered.

Stakeholder	*Desire*	*Regulation Area*
Spectator	Visual divergence	Bodywork Aerodynamics
Spectator	Emotional response to engine sound	power-train
Spectator	Increased dependence on driver skill	Driver-aids †
Manufacturer	Road relevant ('cross-platform') technology	power-train, Electronics
FIA/ OEM	Green branding	power-train
FIA	Safety	Chassis †

Table 6: Summary of how stakeholder desire impacts regulation focus

† Desire to *prevent* regulations from opening up.

Thus power-train and bodywork regulations are therefore two areas most suitable for opening up. Providing an exhaustive list of every restriction removed is beyond the scope of this work but, examples are *"Only 4-stroke engines with reciprocating pistons are permitted"* and *"No bodywork situated more than 1950mm forward of rear face of the cockpit entry template may be more than 550mm above the reference plane."*.

8.3 Preliminaries: Developing a Field of Cars

In order to balance the performance of a field of cars, a realistic set with differing performances is first required. Insufficient data was available to model the car parameters completely, so a combination of the available data, some applied randomness, and vehicle dynamics theory was used. In developing this set of cars, it was important to recognise that changing one car parameter would have knock on implications for other parameters of the car. An example would be that increasing the car's mass, would necessitate a change in spring rates in order to maintain optimal handling characteristics. In order to analyse these relationships a study of race car design and setup was performed, and a model was created in *Analytica.* An influence diagram illustrating the dependencies was then created, which highlighted the difficulty in simulating a field of cars with so many coupled degrees of freedom.

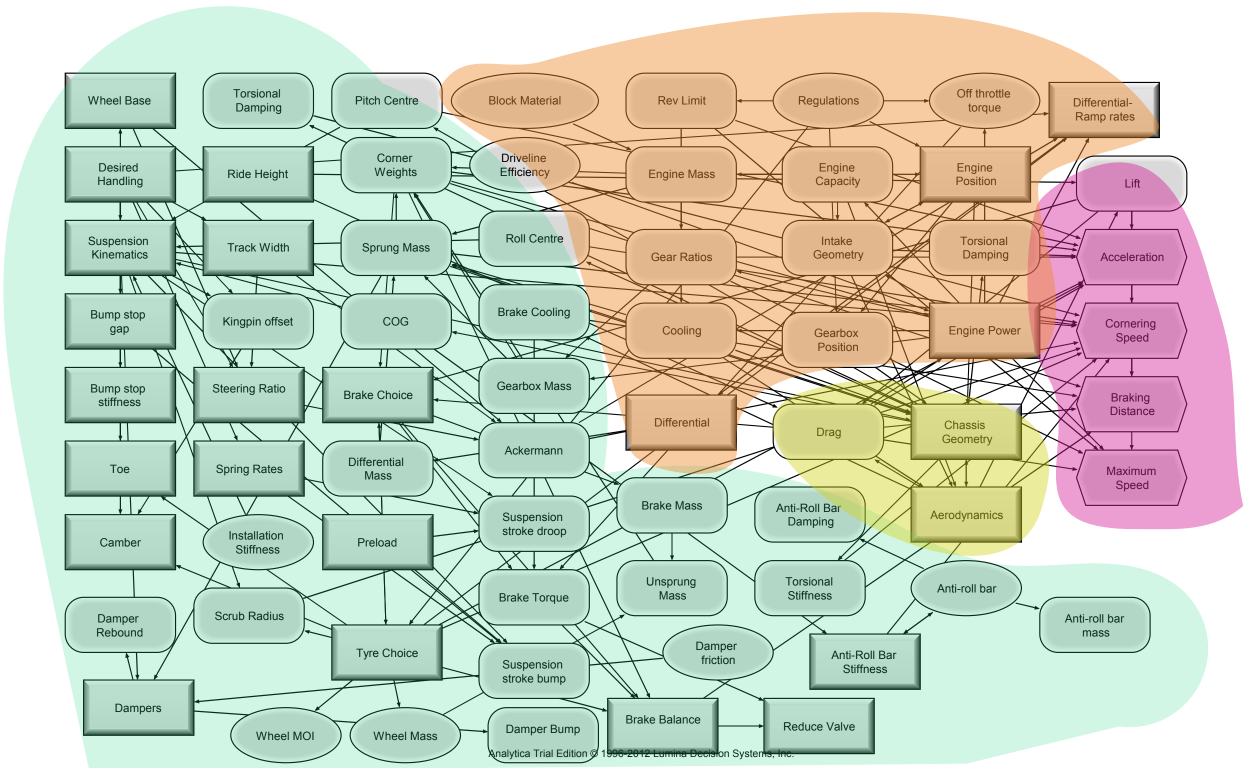


Figure 12: Generic influence diagram for race car design. Blue: Vehicle Dynamics, Orange: power-train, Purple: Performance Parameters, Yellow: Chassis/ Aero

As a result the number of car parameters investigated was significantly reduced. Selection of parameters for the simple model was based around the race car sensitivity to this parameter, and the likelihood that a parameter would vary between cars on the grid. A first-order model to simulate car-setup optimisation was created. This consists of a tree of dependencies (the influence diagram) and a pre defined set of optimisation 'rules' which defines how one parameter changes in respect to another. These rules are functional relationships between different car parameters, derived either from vehicle dynamic theory or otherwise racing 'rules-of-thumb'. The advantage of including the 15 DoF model into the simulation work is two-fold (opposed to only, say, varying mass and power between different cars) ;

1. To prevent unrealistic cars being created. It is unrealistic, for instance, to have two cars of vastly different mass to be running the same set of springs. The model adjusts the springs to fit the mass.
2. The variation in car setup gives rise to a complex set of n^{th} order performance responses, which are difficult to predict otherwise. By including this extra variation, the task of performance balancing deliberately 'complicated' to reflect reality.

The car parameters were generated in serial using a Matlab script, using the process shown below:

1. Power is chosen as an 'independent variable' and initially varied using a randomiser. The bounds on the randomiser are defined by known data.

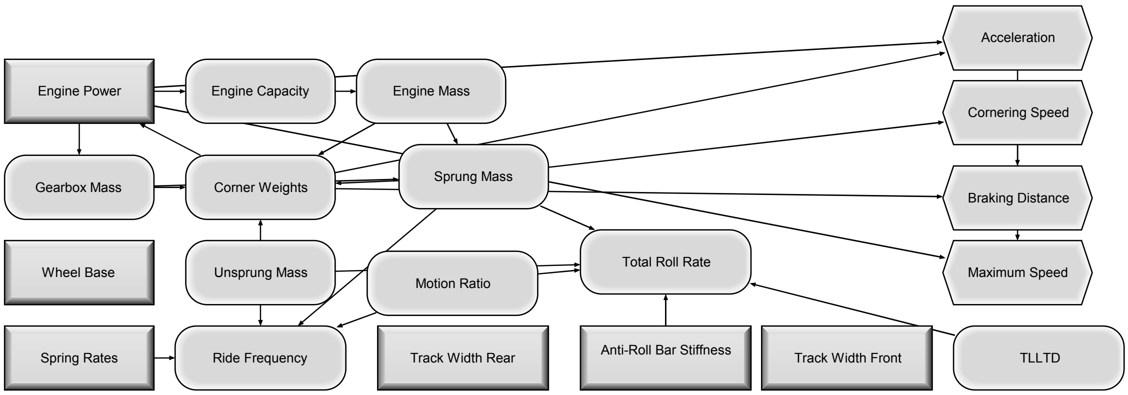


Figure 13: Simplified influence diagram showing 15 DoF model

2. Following the dependencies in the influence diagram, the first order predictions of the optimum values of the dependent parameters are calculated.
3. In order to generate a range in overall performance, an additional randomness is included after determining the optimum value for each parameter.
4. This approach is cascaded through the remaining dependencies in the influence diagram.

Using a combination of optimisation and randomisation a set of cars is developed where there exists an overall trend in performance but, at an individual system level, there is in additional variation (caused by the additional randomness after the optimum parameter value had been calculated). The result is an overall trend of Team 1 the best and Team 10 the worst, but for different individual systems different teams may posses the best/ worst performing systems. The cars modeled were based on *GT3* design data, since the regulation is intended to result in GT3 style design divergence in F1. The relationships used in car modeling are described below;

1. Power is randomized independently. The variation of horsepower on the grid is $\approx 25\%$, which gives the bounds on the randomizer.
2. A correlation between engine capacity and engine power was analyzed from the real data.

$$C = 11.351P - 1340.5$$

   where P is the power (in HP) and C is the engine capacity (in cc). The engine capacities do not fit this trend perfectly and hence a randomiser was used to allow 10% random deviation from this fit.
3. Track width and wheel base vary on the grid at by about 8%, the randomizer was designed to give random variation of 8% around 1.6m and 2.7m respectively
4. Spring rates are related to sprung mass (m_{sm}), the ride frequency (f_r) and the motion ratio (MR) [25].

$$K_s = 4\pi^2 f_r m_{sm} (MR)^2$$

A 'design' ride frequency was chosen of 3Hz [25], and the motion ratio randomized around 0.5. The installation stiffness was allowed to vary by 5%. There is no available data on this, so a conservative estimate was taken.

5. Anti-roll bars were 'optimised' using the relationships [25]

$$K_{\phi FA} = K_{\phi A} N_{mag} MR_{RA}^2 / 100$$

$$K_{\phi RA} = K_{\phi A}(100 - N_{mag} MR_{FA}^2 / 100$$

where $K_{\phi FA}$ is the front anti-roll bar stiffness, $K_{\phi A}$ is the total roll rate, N_{mag} is the Total Lateral Load transfer Distribution (TLLTD), MR_{RA} is the motion ratio. An appropriate TLLTD of 5% forward of the static front weight distribution is chosen [25]. This is a trade-off between limiting over/understeer and preventing instability of the car.

8.4 Simulating FIA Style Performance balancing: 'Control' Method

8.4.1 Introduction To the Method

The FIA method for balancing performance uses a mixture of simulation and track data at the pre season tests. It is split into two phases;

1. *Phase 1: Speed Normalisation.* In phase 1 the v_{max} sensitivity to power is investigated for the fastest car. Once a relationship is determined all cars are fitted to the same function so v_{max} can be normalised for each car by modulating power.
2. *Phase 2: Lap Time Normalisation.* In phase 2 the lap-time sensitivity to car weight is investigated for the fastest car, and using the derived relations all cars are fitted to these functions to normalize Lap Time (LT) and v_{max}.

The form the power sensitivity (v_{max} vs power) takes was derived from theory in order choose the appropriate regression equation. Three forms were found, dependent on the boundary conditions used:

1. *Power limited v_{max}.* In this instance the car reaches (or is close to) a terminal velocity along the straight. The equations of motion give

$$ma = F - kv^2 = \frac{P}{v} - kv^2 \text{ where } k = \frac{\rho C_d A}{2}$$

at the power limited $v_{max} \implies a = 0 \implies P = K{v_{max}}^3$

2. *Rev limited v_{max}.* The car's maximum velocity is defined at the point where the car reaches the rev limiter in top gear.
3. *Distance limited v_{max}.* This scenario results in a v_{max} being reached because there is not enough straight track for either of the other two constraints to be come active. Again

$$ma = F - kv^2 = \frac{P}{v} - kv^2$$

$$a = v\frac{dv}{ds} \implies \int_0^{s_{max}} ds = m\int_{v_1}^{v_{max}} \frac{v}{P - kv^3}dv$$

$$\frac{-3}{km}s_{max} = -\alpha = ln(P - k(v_{max} - v)1)$$

$$P + \frac{e^{-\alpha}}{K} \implies P = (v_{max} - v_1)^3 - \beta$$

where α and β are constant with v.

A preliminary run was performed, it was confirmed that the cars experienced *distance limited* v_{max}. The acceleration was not close to zero (which would indicate power limited v_{max}) nor were the revs reaching the 10k limiter.

Thus the chosen fit for the power v_{max} relationship is a cubic, yielding the following regression;

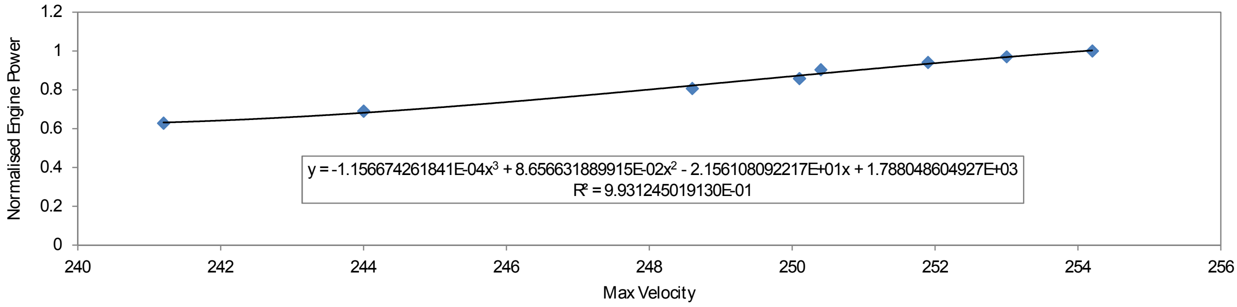


Figure 14: Simulation results from team 1 showing v_{max} sensitivity

A large number of significant figures is needed to fit the regression. It was found that the problem is ill conditioned, and rounding errors in certain coefficients can overwhelm the magnitude of other terms. Power Factor (PF) is here defined as the power of the engine normalised to the power of a 'base' car.

An *equivalent power factor* is calculated from the values of v_{max} and the relationship derived. This equivalent power is the power a car would have, if it were otherwise identical to the fastest car and have the same v_{max} result. The power adjustment required to converge v_{max} for each team to the slowest car is then calculated from this (the *required* power factor).

8.4.2 FIA Balance Phase 1 Results

The results show a reduction of variation in v_{max} from around 10kph to around 3kph, ie. phase 1 was a success, by the standards of the FIA (section 4.3.4).

8.4.3 FIA Balance Phase 2

The next phase requires modulation of the car weights in order to normalise the lap time. The weight sensitivities were measured for team 1 as with power, and show an excellent linear fit. It can be seen that the weight modulation will also cause a change in v_{max} (in fact m appeared in the final derivation of v_{max}), distorting the already normalised set of velocities.

Team	v_{max}	*Equiv. PF*	*PF Req.*
Team 1	254.2	1.002583416	0.692255024
Team 2	254.3	1.005243613	0.690423095
⋮	⋮	⋮	⋮
Team 9	244.5	0.694043407	1
Team 10	246.7	0.758282533	0.915283389

Table 7: Selected results of first analysis predicting power adjustments required to normalise v_{max}

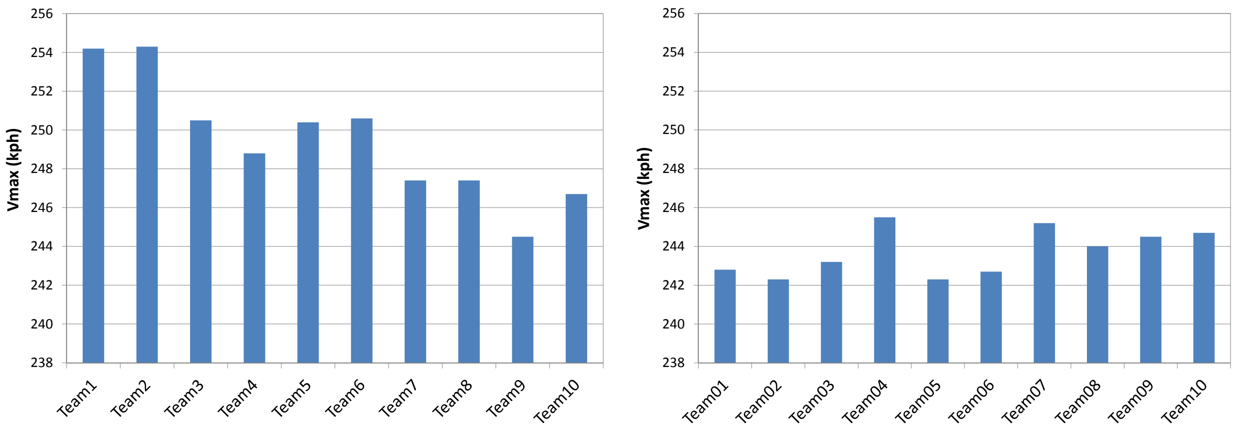


Figure 15: Before (left) and after (right) v_{max} *for each car in the field*

The real world application of this method would require a degree of intuition and iteration. In this work v_{max} and lap time are minimised together using the solver functionality in excel. The amount of ballast (ie. car mass) is varied to achieve this.

Formally, the problem is cast as an optimisation exercise. The objective function consists of the standard deviations of both lap time and v_{max}, predicted by the empirically derived relationships with power and mass, normalised to their respective averages to give equal weighting. The solver [9] is allowed to alter values for both mass and engine power. The feasible region is constrained to 'realistic' deviations in power and mass hence;

$$\underset{x}{\text{minimize}} \qquad f(x) = f(v_{max}, t_{lap}) = \sum_{1}^{N_{teams}} \frac{\sigma_i(t_{lap})}{\overline{t_{lap}}} + \frac{\sigma_i(v_{max})}{\overline{v_{max}}}$$

$$\text{subject to} \qquad 1 < m < 1.2$$

$$\text{where } v_{max} = f(m) \text{ and } t_{lap} = f(m)$$

m and p are the mass and power factors respectively.

8.4.4 FIA Balance Phase 2 Results

The results of the second (and final) phase of the FIA performance balancing are summarised in the table below

[9]The excel solver uses the reduced gradient method for optimisation.

Parameter	*CoV before balance*	*CoV following balance*
v_{max}	0.022	0.0025
Laptime	0.012	0.0060

Table 8: Before and after analysis of the FIA performance balance method

The FIA method after a single pass, normalises lap times and v_{max} well, but this degree of normalisation is not adequate for F1. Other algorithms of performance balancing with mass and power were developed instead.

8.5 Improving the performance balance: The 'One Shot' methods

One limit in the efficacy of the FIA method is that the performance parameters are balanced in serial, ie. v_{max} is balanced during phase 1 by varying power, in phase 2 lap time and v_{max} are balanced by varying mass/ ballast. As a result available solutions during phase 2 are limited as power is not modulated, it is therefore highly likely that minima are missed. The purpose of the 'One Shot' methods are to ensure that the whole performance surface is explored during phase 1 by finding the lap-time sensitivity as *both* weight and power are varied simultaneously, and similarly for v_{max}. The optimisation exercise then minimises lap-time and v_{max} together, by varying mass and power together- ie. optimisation in one shot. A number of variants following this procedure, but with differing objective functions, were developed in response to the observed second order effects. These are summarised below;

1. *'Vanilla One Shot'.* In this method the objective function remains the same as in the FIA balance. The difference lies in the fact that the lap time and v_{max} are now 2 dimensional functions of both mass and power, hence

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) = f(v_{max}, t_{lap}) = \sum_{1}^{N_{teams}} \frac{\sigma_i(t_{lap})}{\overline{t_{lap}}} + \frac{\sigma_i(v_{max})}{\overline{v_{max}}} \\ \text{subject to} \quad & 1 < m < 1.2 \\ & 0.8 < p < 1.0 \end{aligned}$$

$$\text{where } v_{max} = f(m,p) \text{ and } t_{lap} = f(m,p)$$

2. *'One Shot: Static Average'.* The objective function used in 'Vanilla' one-shot uses average lap-time and v_{max} to normalised the standard deviations of each, in order that they have the same contribution to the objective function. The disadvantage in this however, is that the average lap time and v_{max} become part of the optimisation, and the search is skewed by maximising these quantities (the denominators). In the static average method the denominators are replaced by constants which approximately perform the same task

but do not skew the direction of search, the new objective function is:

$$\underset{x}{\text{minimize}} \qquad f(x) = \sum_{1}^{N_{teams}} \frac{\sigma_i(t_{lap})}{60} + \frac{\sigma_i(v_{max})}{200}$$

3. *'One Shot: Faster Cars (extra constraint)'.* The principle of the faster car methods were to add an extra consideration, that the performance balancing should not significantly reduce the speed of the cars that would otherwise impact on the spectacle. The first method used a constraint that the cars should converge to the speed of approximately the slowest unbalanced car;

$$\begin{aligned} \underset{x}{\text{minimize}} \qquad & f(x) = \sum_{1}^{N_{teams}} \frac{\sigma_i(t_{lap})}{60} + \frac{\sigma_i(v_{max})}{200} \\ \text{subject to} \qquad & 1 < m < 1.2 \\ & 0.8 < p < 1.0 \\ & v^i_{max,balanced} \approx v^{min}_{max,unbalanced} \quad \forall i \\ & t^i_{lap,balanced} \approx t^{max}_{lap,unbalanced} \quad \forall i \end{aligned}$$

4. *'One Shot: Faster Cars (penalty function)'.* An alternative to applying an additional constraint, is to introduce a penalty function to apply a cost of the search optimisation producing solutions which are slower than they need to be

$$\begin{aligned} \underset{x}{\text{minimize}} \qquad & f(x) = \sum_{1}^{N_{teams}} \frac{\sigma_i(t_{lap})}{\overline{t_{lap}}} + \frac{\sigma_i(v_{max})}{\overline{v_{max}}} + \left(\frac{220}{\overline{v_{max}}} + \frac{\overline{t_{lap}}}{60}\right) \frac{1}{2} \frac{1}{0.00105} \\ \text{subject to} \qquad & 1 < m < 1.2 \\ & 0.8 < p < 1.0 \end{aligned}$$

8.5.1 One Shot Method Procedure

For each of the one shot methods the procedure is the same.

1. A matrix of 36 variants of the fastest unbalanced car is generated with mass and power varied by 20% either side of a base value.
2. A simulated lap of each of these cars is run
3. The v_{max} for car in the matrix is then used to generate a surface with v_{max} a function of mass and power. Likewise for t_{lap}.
4. A 2D regression analysis is performed to yield the underlying relationship
5. This regression function is then used to predict how t_{lap} and v_{max} changes for every car in the field as power and mass are varied

6. The average and standard deviation predicted values are then used in the objective function, and the solver is allowed to vary mass and power
7. The new grid of balanced cars with appropriate mass and power modulation are then simulated to confirm the results

The generated surface of performances is shown below

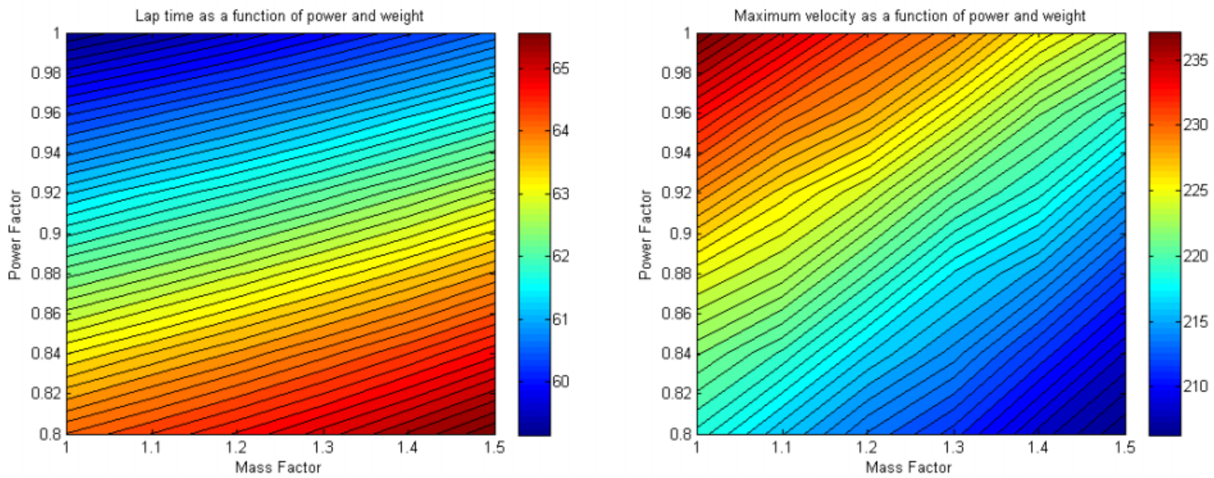


Figure 16: Performance surfaces for v_{max} and laptime

From this surface, linearised regression equations for lap time and v_{max} are found using the Excel regression solver:

$$v_{max} = 67.26 f_{power} - 35.70 f_{weight} + 205$$

$$t_{lap} = -7.402 f_{power} + 10.03 f_{weight} + 56.58$$

8.6 Results

8.6.1 Efficacy of Balance

A comparison is made between the different methods below. Approach 3 (One Shot: Faster cars) was omitted as the optimisation algorithm failed to converge.

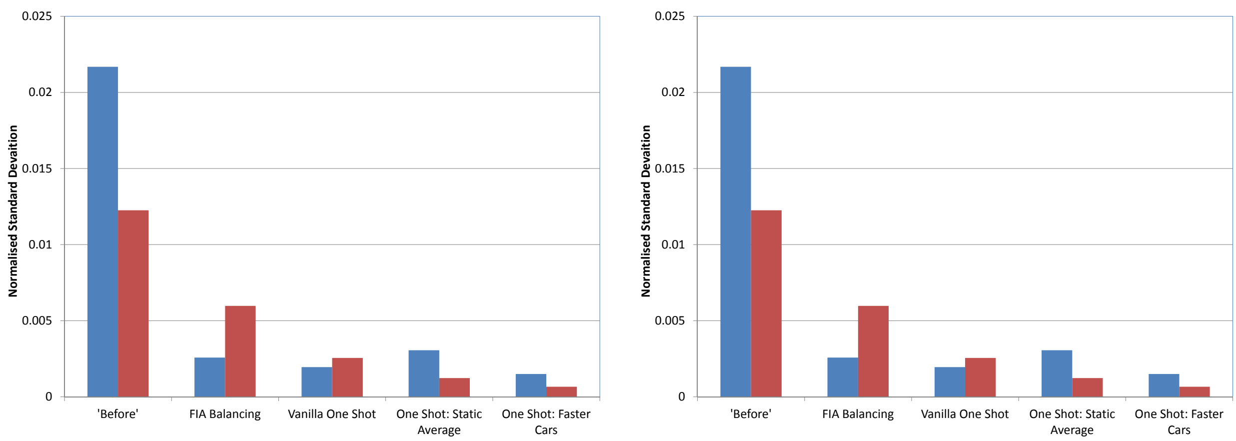
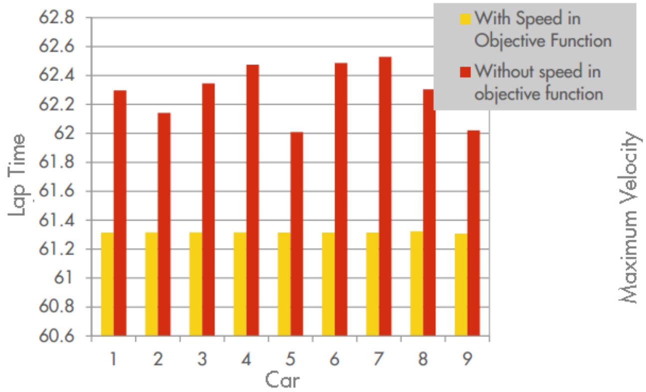


Figure 17: Comparison of balancing methods with two different measures of spread. Blue: v_{max} Red: t_{lap}.

The results show that each of the one shot methods has better balancing characteristics than the FIA balance. The differential between the one shot approaches is small, but it appears the 'faster car' variant is the most effective algorithm. This is a surprising result; the optimisation search is complicated by additional terms in the objective function. It is likely second order effects are influencing the result.

8.6.2 Faster Cars

One of the stated aims of the faster cars variant was to prevent the optimisation search from causing an overly slow grid. A comparison was made between the balanced car performances for the one shot faster car method, with the vanilla one shot method. The results clearly show this objective was achieved.



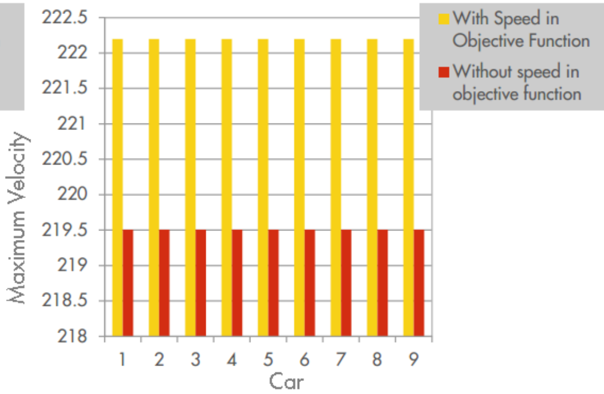


Figure 18: Comparison of t_{lap} (left) and v_{max} (right) after one-shot performance balancing with and without 'speed' optimising objective function.

8.6.3 Track to Track Variability

A final question on the effectiveness of performance balancing, is that the balance is performed at a single track, but the season spans a wide variety of track layouts and conditions. A successful performance balancing technique should be robust to such changes- the balance should not be lost when a new track is visited.

An investigation into how performance balancing is affected as the car's performance is normalised for one track (in this case Hockenheim), and throughout the season different tracks are visited. The tracks used were:

- Hockenheim[10]. Fast corners, and short straights characterise this version of Hockenheim.
- Barcelona. This track contains a mixture of a long straight, some fairly slow chicanes and reasonably fast sweeping bends.
- Monza. A very fast track, long straights and fast corners with some slower chicanes.

[10]The Hockenheim model is much less an accurate representation of the true track than the others.

- Hungaroring. A slow, tight and twisty track with very little in the way of either a substantial straight or fast corners.

The charts show how the variability in car performance changes after different tracks are visited after first normalising the performance in Hockenheim. The two measures of grid variation are used, the static average one-shot and faster car method were used for comparison.

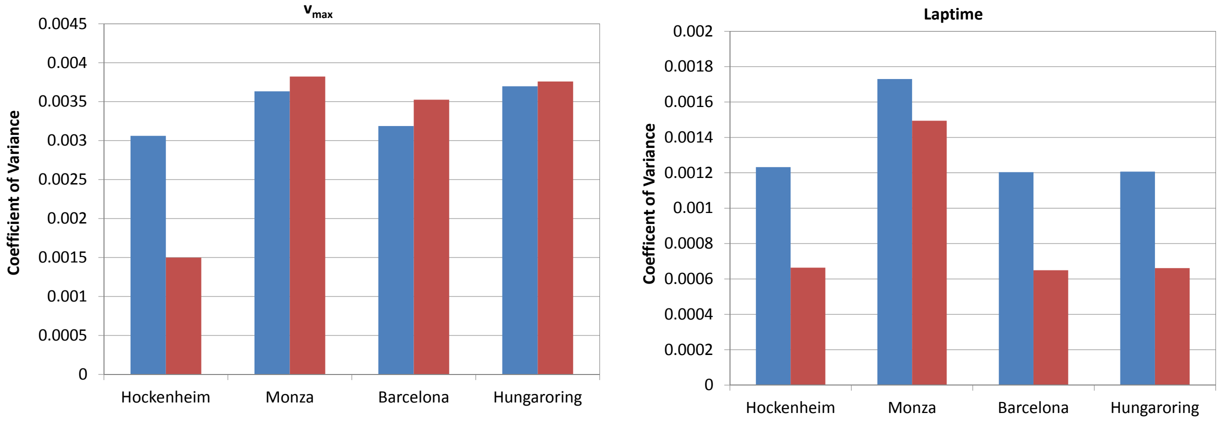


Figure 19: Effect on performance balance of visiting different tracks in a season showing how the balance is skewed with track changes. Blue: 'Static average', Red: 'Faster car'

The results show that the effect of balancing at one track and moving to other tracks is to skew the balance by between 0 and 100% depending on the track, and parameter considered. Interestingly there is only a very tiny impact in lap time CoV (around 1%) when moving from Hockenheim to Barcelona and Hugaroring, visible only in the numerical results. It is not clear why this should be the case.

To put this in context, a CoV of 0.001 implies a standard deviation of nine 100$^{\text{th}}$s of a second around a 90 second lap. A CoV of 0.002 imples a standard devaition of 0.4mph for a nominal v_{max} of 200mph. Similarly the calculated spread over the whole field (before driver effects are taken into account) was 0.36s, and 2mph with the same nominal conditions.

8.7 Conclusions On the Introduction of Performance Balancing into F1

It was possible to create a framework whereby the design space was greatly expanded by simply removing large sections of the geometrically restrictive regulations. The proposed method of removing the desire to spend was performance balancing which would have the result of new technical development having no lasting performance gain. Manufacturers are then allowed to focus on specific technical objectives, for instance meeting the brand objectives of the OEM's. This was made possible by developing a more sophisticated approach to performance balancing than the FIA GT3 methodology.

In order to develop this method further, an improved procedure for performance balancing was sought and the most effective method was shown to be the 'one-shot: faster car' method.

This would result in a t_{lap} spread of 0.36s and v_{max} spread of 2mph, over a nominally 90s lap with 200mph top speed. The wider implications of implementing performance balancing in F1 are now considered.

8.7.1 Technical feasibility

The investigations in this project looked at two strategies to normalise performance between different cars, namely by modulating the *mass* and *engine power*, with the former requiring the addition of ballast and the later the use of a restrictor plate.

- FIA enforced ballast. F1 cars have been using ballast (by the team's own choice) for decades, and hence knowhow and technologies to ballast and F1 car already exist, ballast is a 'mature technology' in this respect. The maximum normalising ballasts which the simulations suggested were 20% of the car weight [11], 130kg of ballast would be required. In a modern F1 car around 30 Kg of ballast are used [27], and hence a significant rethink of car packaging would be required, this has cost implications.
- FIA enforced restrictor plate. The technical difficulty in implementing a restrictor plate is not the restrictor plate itself (Torro Rosso used a restrictor plate by choice in 2008), but in managing to modulate the engine power to the desired level. A restrictor plate will limit the mass flow of the air through the orifice by preventing the velocity from increasing beyond the sonic velocity and therefore reducing the rate of Mass Air Flow (MAF) increase with pressure ratio. This relationship is shown below;

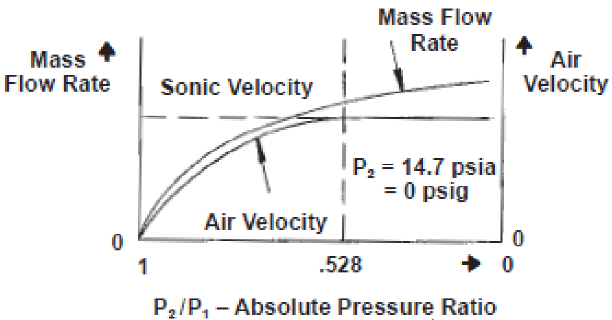


Figure 20: Choking effect at large absolute pressure ratios (and hence open throttle conditions) [28]

Under choked flow conditions the mass flow rate follows the relationship below where p is the *upstream pressure*, k the heat capacity ratio, ρ the density, A the area and C the specific heat capcity [29].

$$\dot{m} = C\,A\sqrt{k\,\rho\,P\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$$

This relationship highlights two important technical difficulties in applying a performance normalising choke as part of an F1 intake system. Firstly a dependence on ambient conditions

[11] In 2012 all the cars weighed 650kg.

(air temp, humidity) is seen in the specific heat capacity and density terms. Two cars with normalised performance under certain ambient conditions, will not necessarily be balanced as these conditions change. Secondly choking of the air flow only occurs at high pressure ratios, and hence wider throttle conditions. Thus the impact on engine performance is not uniform across the power curve and as such will differ between engines, tracks, and drivers. The chances that the governing body can implement restrictors in order to modulate engine performance with the accuracy that would be required in F1 for a 'fair' performance handicap are therefore slim. An interesting counter proposal would to be to run the restrictors in 'closed loop'. The FIA are however looking at flow control to modulate engine power, but with fuel restriction for the 2014 regulations. This could provide another degree of freedom when trying to modulate power, and avoid some of the problems encountered with air restrictors.

8.7.2 Desirability

There is significant evidence that the main stakeholders in F1 (the fans, teams, FIA etc.) would not find the introduction of performance balancing a desirable outcome. Performance balancing runs contary to the FIA description of the 'DNA' of the sport:

"The concept that the best team, with the best combination of car, team and driver will emerge as Champion." [33]

Similarly, the spectators, of which around 80% desire the best driver/ team combination to win (table 2) are also likely not to be satisfied by the concept of handicapping drivers purely as a result of them performing well. This desirability is relaitve however. If it proves impossible to control costs by other means, it may prove a useful method of last resort. In this situation the alternative the FIA could face is that major motorsport marques (Ferrari, Mercedes, McLaren etc.) leave the sport.

9 Regulation Development: Proposal 2

In the second major investigation, proposal regulation 2 is considered. The proposal states that the regulations would reveal a set of regulations at the end of each season which permitted 3 competing technologies, with equal performance characteristics and the development time (and therefore spend) would be limited by introducing a moratorium on the introduction of new parts at the first race. The regulation is therefore developed in two stages. First, the competing technologies which are to be permitted are defined by considering how best to meet the additional requirements of the regulation (section 3), and second, appropriate normalising of the performance of each technology is performed. These two phases would be repeated each year and in this proof of concept only a one year cycle is considered.

9.1 Stage 1: Defining the Regulation

The selection of the permitted solutions gives scope to meet the full set of requirements outlined at the start of this work. Therefore the technological choice should be one which is pro-overtaking (fan desire), acts to benefit a 'green' branding of the sport (FIA desire) and promotes development in areas which OEM's are already committing resources (OEM desire). These requirements suggest a solution set encompassing power-train technologies would be suitable.

9.1.1 Continuously Variable Transmission (CVT)

The CVT technology is an alternative form of gearbox arrangement, whereby a fixed set of gears (typically 7 in F1), is replaced by a mechanism which effectively has an infinite number of ratios. A number of solutions exist, one of the simplest consists of a steel belt and a set of 2 conical pulleys (input and output shafts). The gear ratio is controlled by changing the relative radius of the pulley by moving the cones in and out. This arrangement is shown below.

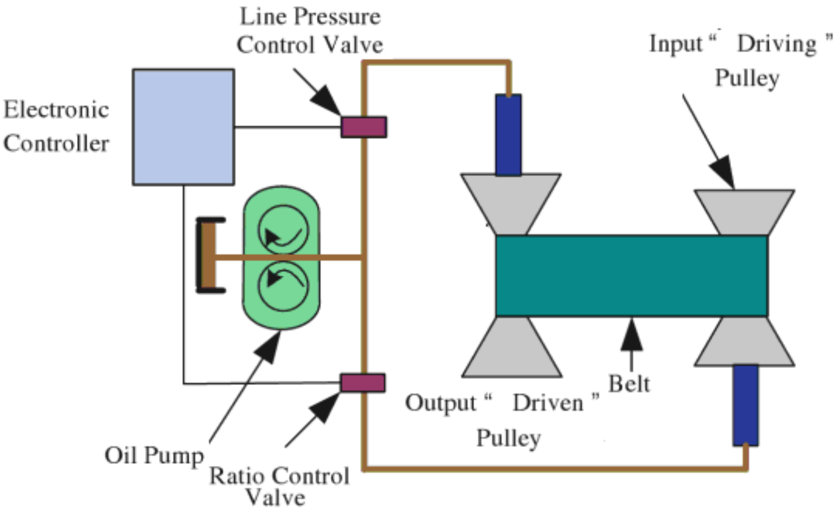


Figure 21: Belt and Pulley CVT arrangement [35]

Different solutions also exist favoured by different OEM's, multitronic (Seat), Toroidal (Nissan) and Power Split Transmission (Toyota) [12]. The advantage of using a CVT is it allows the constant running of the engine in a more efficient torque band as an infinite number of road speeds can map to a single engine speed. In road car technology this has obvious environmental benefits (although the efficiency of the CVT's themselves need some improvement) and in Formula One a performance benefit exists by running the engine at the peak of the power curve at all speeds. The ban on in-race refueling magnifies this effect, any technology which reduces fuel consumption effectively yields a weight benefit.

[12]This implies one could expect a degree design divergence simply by the introduction of CVT into F1 regardless of other considerations

9.1.2 Energy Recovery System (ERS)

The ERS system is a conceptual extension of the Kinetic Energy Recovery System (KERS), already used in F1, planned for introduction in 2014. The ERS system would allow generation of electrical energy from both braking (where the energy would otherwise be dissipated as heat) and from the exhaust gas velocity. The power is then delivered through an electric motor (typically Brushless DC (BLDC)) in either 2 or 4 of the wheels.

In racing terms this means otherwise wasted energy can be used to generate additional power, whereas in road car technology it acts as another fuel efficiency technology. The technologies developed in the ERS system are relevant to road car technologies, where hybrid vehicles are developed. The investment into developing the hybrid market has increased enormously in recent years, evidenced by the projected growth in hybrid sales shown below

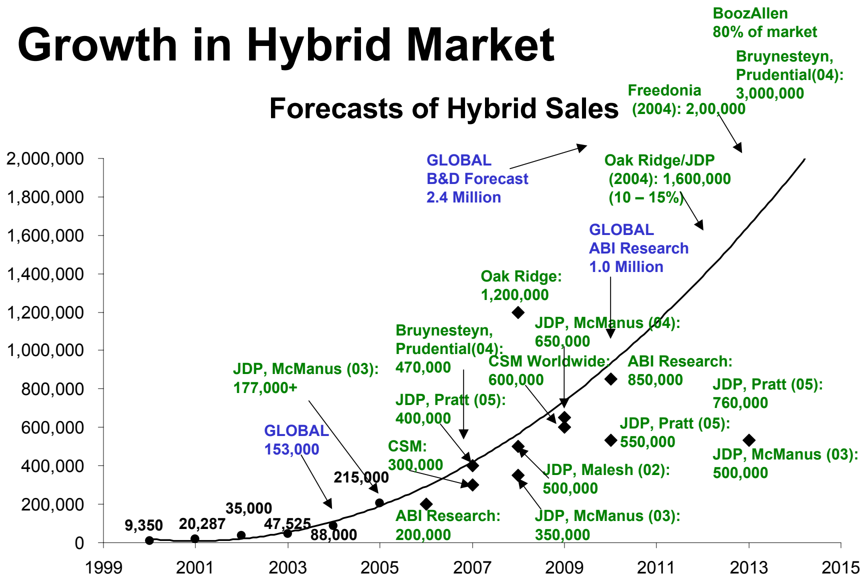


Figure 22: Projected growth in Hybrid sales [36]

OEM's therefore welcome the introduction of ERS technologies, and the synergy between the racing and R&D budgets makes F1 financially more attractive.

As evidence to the desirability of this outcome, the FIA are introducing a series of measures in the 2014 technical regulations to encourage R&D knowledge transfer between road and racing car. An example of this is turbo-compounding where waste energy in the form of exhaust gas velocity directly powers the crankshaft. When permissible in F1, the belief is that such research could lead to the wider introduction as a road-car technology.

9.1.3 Conclusions and Definition

From this brief discussion there is reason to believe introducing ERS and CVTs as two solutions permitted would satisfy the desires of the FIA and OEM's. A third permitted solution is implementing neither technology, but with a reduced minimum weight. This presents an interesting prospect in terms of overtaking- one would expect a performance differential in favour of ERS *out* of the corner, and performance differential in favour of the 'light' car on braking *into* the corner.

Thus the regulation is proposed;

"The regulations permit 3 power-train variants- Kinetic Energy Recovery System (KERS), Constant Variable Transmission (CVT), and conventionally powered drivetrain. The minimum weight is adjusted depending on the power-train selected"

The minimum weight limit is used as the 'balancing' factor between these technologies, and hence similar methods discussed in the performance balancing discussion can be used. It is important to realise that thiis procedure *does not* expose the regulation to the undesirability implications of performance balancing discussed previously. In this proposal weight is used to balance the inherent technological performance, rather than team performance. As a result, individuals are not being punished for performing well, which was the fundamental issue with GT3-style performance balancing.

9.2 Stage 2: Formulating the Balanced Framework

Using similar techniques as in proposal 1, the proposed permitted solutions are balanced by altering the minimum weight for each until any solution yields the same lap-time. Similar to previous investigations a matrix of 18 cars was developed with similar properties but varying in mass and their technology;

power-train	Normalised Masses					
CVT	0.90	0.95	1.0	1.05	1.10	1.15
ERS	0.90	0.95	1.0	1.05	1.10	1.15
Conventional	0.90	0.95	1.0	1.05	1.10	1.15

Table 9: Technology performance balance matrix

This matrix of cars is then run over a single lap at the Barcelona track. This procedure followed the batch running of simulations that was used in previous investigations, but with some alterations. To simulate CVT this is set in the RaceSim engine file, and causes the engine to maintain peak power output, and the gear ratio tracks the road speed. In order to simulate the decrease gearbox efficiency which would be expected when operating a CVT, the driveline efficiency was reduced by 10%. The ERS simulation is more complex, in these investigation the KERS simulator inbuilt into RaceSim was used. In order to simulate the 'strategy' of where KERS power is released, two runs are required. In the first run the simulator harvests energy and calculates the optimum release points. This data is written to a KERS track-file, which lists the quantity of KERS release (in Joules) for each section of straight. The KERS mode is then changed, and the simulator runs the car, applying KERS at the optimal points around the track. The total energy storage by the KERS system and motor power are free variables, and these were tuned so that appropriate balancing could take place. 500kJ was used as capacity, and 60kW as maximum motor power. This compares to 600kJ and 60kW permitted in the 2012 technical regulations. An constant performance contour was chosen, and appropriate minimum weights permitted for each car as, shown below

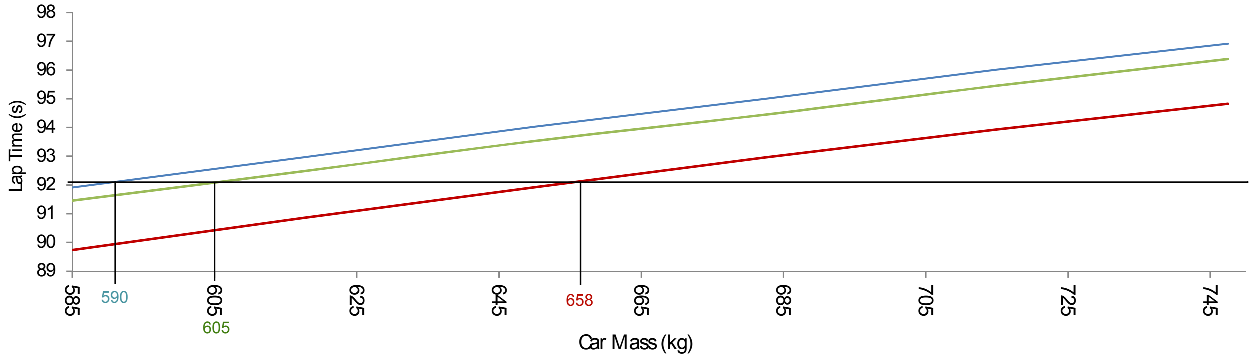


Figure 23: Permitted minimum weights are chosen for each technology by choosing a constant performance contour. Blue: Conventional power-train, Green: ERS, Red: CVT.

9.2.1 Robustness

As previously discussed, for performances balanced at one track, there must be robustness as different tracks are visited. The three cars designed in the previous section were simulated at different tracks to investigate this. The following question was posed;

If the solution's performances were balanced at one track (Barcelona)- would they stay balanced over the course of a season?

Barcelona (exhibits long straights, and mix of fast and slow corners), results from Monza (fast), Hungary (tight and twisty) and Hockenheim (moderate) were used as comparisons.

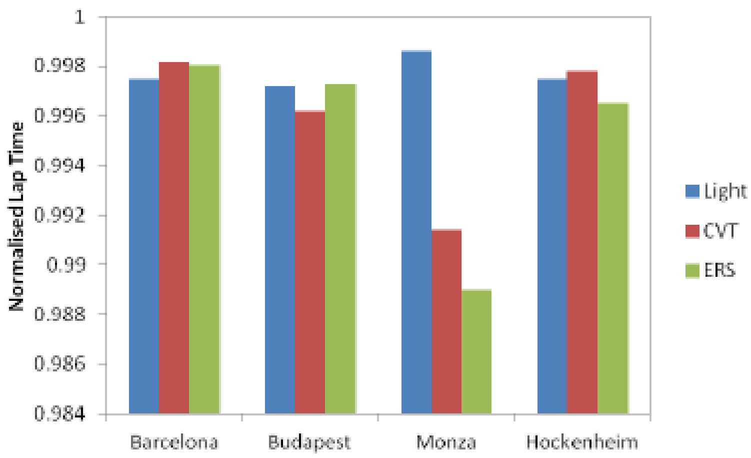


Figure 24: Lap times for each solution after performance balance at Barcelona

The results are compelling- they show that for nominally balanced performance at Barcelona, the worst performance imbalance is $\approx 1\%$ of the laptime or 0.8s. Hence with improved development the using data over numerous tracks worst performance deviation could likely be reduced to below 0.5s. More importantly the results show that different technologies 'win' at different tracks, this is desirable both OEM and spectator. The effect is to create more exciting championships, with a wider variety of winners and allowing each technology its 'day in the sun'.

The limitations of the lap-time simulation however, may over-simplify this analysis. Other effects (tyre degradation, fuel economy etc.) may begin to skew the balance. The FIA would therefore be advised to 'tweak' the regulations mid season to account for this. There is already precedent for mid-season rule changes, although it often brings some degree of controversy. These issues are discussed in detail during further work.

9.3 Further Implications of Discrete Parametric Regulation

The purpose of the following discussion is to consider what the other relevant factors are when the choice of permitted technologies is being made each year (phase 1), and developing the methods the regulator could use to make these considerations.

9.3.1 Overtaking

To make an approximation of the propensity of these solutions to promote overtaking, speed deltas were taken over the whole lap. The data required the implementation of an interpolation algorithm to avoid 'phasing noise' in the delta signal. This noise is caused by the RaceSim data logger sampling at different points on the track for the different runs, ie. the n^{th} sample is not at the same point on the track for each car, and so the speed delta at the n^{th} data point is otherwise skewed by this difference.

The results are promising, speed deltas between the different solutions are regularly over 10kph around the track. By comparison the Overtaking Working Group (OWG) designed the Drag Reduction System (DRS) to yield a 12kph speed differential in order to promote overtaking. The most prominent effects are the spikes caused by braking into the corner, cars of different weights have a large effect on where drivers pick their braking zone and hence the speed differential during the earlier phases of braking. In addition the power-train difference affect the speeds on *exit* of the corner, with the KERS car producing a delta magnitude of roughly half that deficit it experiences under braking. The results therefore predict one would observe a light car overtaking into the corner- only to be re-overtaken on the exit, at around half of the corners on the track!

A more detailed *local* analysis was then considered by designing single, specific corners in

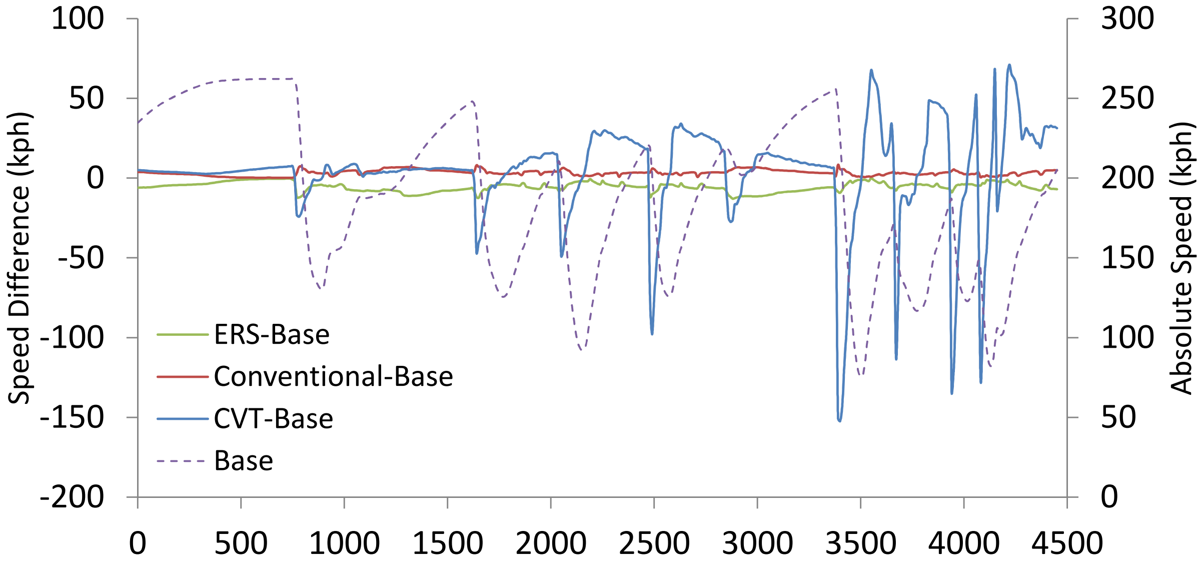


Figure 25: Speed deltas compared to a 'base' vehicle (650kg, conventional power-train). Absolute speed shown for base (dotted) on right axis.

RaceSim and observing the speed profiles for each type of corner, the forms investigated were; Open Turn, Tight Hairpin, Open hairpin/ parabolica and S-Bend. The results supported the conclusions drawn from Barcelona data. The more subtle results came from the 'Open turn', by far the fastest corner investigated (around 250 kph), where the lighter car was faster compared to the KERS car in the whole duration of the corner (the speed is grip limited in the turn), but the CVT was faster than either case due to better rev matching. Thus it is seen how the number of fast corners to heavy braking/ acceleration corners affects the probability of a particular solution winning.

In order to more easily analyse how the relative performance of the cars evolved around a corner the data was animated. A Matlab script was written which imported data from RaceSim, interpolated the position samples and produced positioned marker on the screen. By producing a series of frames, a short animation of the cars jostling for position in the corner was generated.

9.3.2 Driver Difficulty

Specification 2 requires the regulation should emphasise driver skill. An additional route to achieving this is to make the racing appear more difficult. There has been recent criticism that F1 car's *look* 'too easy' to drive [38]. This is primarily due to improved driver fitness more predictable car handling, but the criticism is on the appearance rather than suggesting F1 has become easier. In order to improve this appearance the regulator should choose technologies(during stage 1) which maximise the apparent difficulty of driving the car. This has been divided into forms; cerebral difficulty (the driver must react to many different events during the race), physiological difficulty (the driver appears physically drained after leaving the car), control difficulty (the driver appears very busy in the cockpit controlling the car).

The increase in overtaking already discussed is likely to increase the cerebral difficulty.

The proposed procedure in order to determine the control difficulty analyses the number of operations, gear shifts, throttle position changes etc. required by the driver during a race. This analysis was performed on the CVT/Conventional/ERS power-train solutions described thus far.

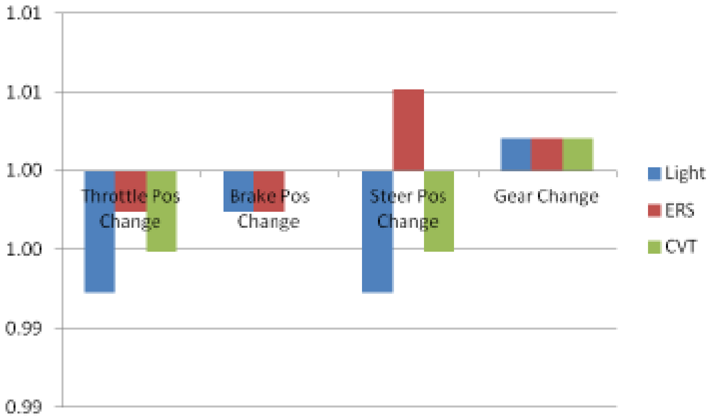


Figure 26: Normalised control difficulty with CVT/ Light/ KERS solutions. A value > 1 *indicates increased difficulty.*

A study on the available literature regarding driver fatigue drew conclusions that at a first approximation, fatigue is a function of average heart rate which is affected by four main factors; anxiety, core temperature, vibration and G-force [40] [41]; but not by top speed. These data are included in the simulation results, so a simple comparison of how altering car designs affects driver fatigue is trivial (to first order).

10 Conclusions

The aim of this project was to develop a regulatory framework which would encourage design divergence within F1. The original scope was to consider how this could be achieved by introducing parametric regulation, but this was extended in order to consider a wider range of mechanisms which promote design divergence. It was argued that there is a desire within the stakeholders of F1 for increased design divergence, a number of other desirables were also considered to produce a list of requirements for the framework.

Evidence for divergent mechanisms both within and outside F1 were considered. An analysis of how regulations affect the competitiveness of GT3 and F1 was performed. This showed performance balancing kept GT3 competitive, even with a large range in car models entering. In F1, the 1980's was shown to be a particularly comeptitive era. A discussion was made on how best to remove the desire to spend, identified as a key factor in the success of any regulation promoting design diversity. Using this analysis two proposed regulations were formed; (a) Open Regulation with Performance Balancing and (b) Discrete Parametric Regulation. In order to apply performance balancing the methods used by the FIA currently (in GT3) required refinement. A number of variants were investigated with the method 'One Shot: Faster Car' proving the most effective. A spread of 0.36s over the lap and 2mph top speed was predicted. After consideration of all of the implications of performance balancing, although technically feasible a critical flaw was that it runs contrary to the 'DNA' of the sport, and hence does not meet a key requirement.

The second proposal was devised following a promising lead in the performance characteristics when the 1980's were considered, where a mechanism similar to parametric regulation was introduced. Teams are permitted one of a discrete number of technological solutions. By limiting the time the teams were permitted to develop the car, a safegaurd is incorporated to cap any increased desire to spend that might result. A consideration is given to how the choice of permitted technologies could meet the other requirements of the regulation, the desire for increased environmental sustainability and road-car relevant technologies. As a result the CVT and ERS systems are used as the proposed technological solutions. Using weight as a balance of performance in the technology in order to maintain competitiveness (requirement 2), meant that each of the technologies had roughly similar performance which would prevent design convergence to a single solution. A number of interesting second order effects were also discovered. At different tracks, different technologies had a slight edge, and so different technologies get 'a day in the sun'. This was suggested as a very attractive prospect for OEM's. Furthermore the effect of different masses and power-trains meant that the propensity for overtaking was significantly increased. Under-braking speed differentials of around 10kph were visible (enough for an overtake). This speed advantage reversed under acceleration suggesting cars close enough would perform two overtakes (an overtake, and then position regained) for around half the corners on the track. A method for animating the data was devised to confirm this. It is for these reasons that the second proposed framework is the proposal as the conclusion of this work.

11 Further Work

11.1 Developing Proposal 2

11.1.1 Tyre Degradation

One consideration on the choice of permitted solutions which has not been investigated is that of the effect on tyre degradation. This was omitted because the requirements to accurately model the effect of permitted solutions on tyre degradation are far beyond the scope of this work. In some areas the understanding simply does not exist to analyse this properly. RaceSim outputs a variety of predicted data, and a relationship between those parameters and the tyre degradation would need to be found, ie.

$$\text{Degradation} = \int f(\text{slip angle}, F_y, F_x, F_z, ...)dt$$

A literature review was conducted to determine if such models already exist, but none suitable could be found. Performing analyses of tyre degradation profiles extracted from race data was also considered, where changing fuel load would act as a changing car weight variable. It was decided there are far too many dependencies to extract this relationship successfully however. It is likely a collaboration with Pirelli would be required, as much of the knowledge is proprietary.

11.1.2 Car Setup Variation

The balancing of the performance of different permitted solutions in proposal 2, as only a proof of concept, has not taken into account the effect of adaptive set up changes. Clearly with the addition of mass the spring rates, dampers etc. would be changed on the car after performance has been balanced, skewing the results. Further work into either developing a model with optimises the car setup during the simulation balancing process, or otherwise investigating the performance sensitivity surfaces at different points on the design surface and designing the regulation such that the performance is in-sensitive to setup changes. An example comparing the performance sensitivity (ie. the gradient of some performance metric) at different absolute values of spring rates and damping ratios was used as an example, shown below.

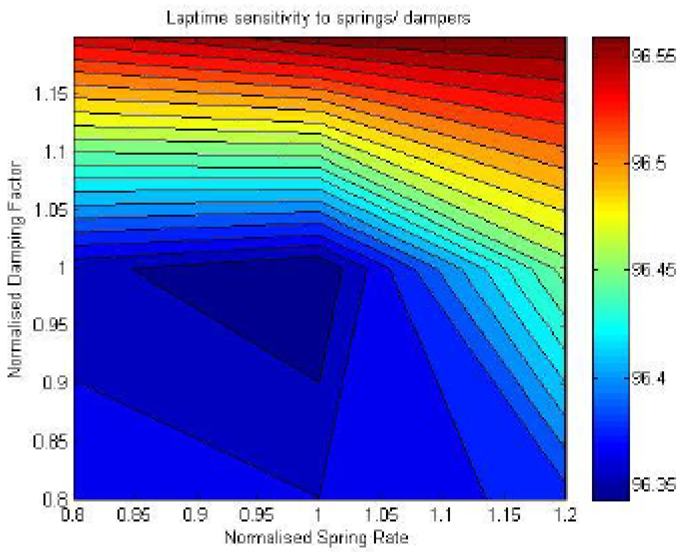


Figure 27: Laptime at different values for spring rates and damping ratios, normalised to standard values

In this example, lower damping ratios yield a performance 'plateau' and thus the performance exhibits less sensitivity to deviations in car setup.

11.2 Future Solutions Permitted

The regulation given only delivers the *first* set of technological solutions. Future regulations (by the definition of the framework) would require a new set of solutions permitted each year. Further work to plan out future regulations would be of worth.

11.3 Additional Proposals

Some proposals which were considered during this work, have not been in the final report. Investigating these would provide interesting results. An example is ‘open source’ F1, whereby new technological developments are published for all competitors to see. This approach is being tried in the ‘delta wing’ project for Le Mans. Whether open source racing could be used to remove the desire to spend, whilst opening up the design space to encourage a diversity in design.

12 Risk Assesment Retrospective

The risk assessment conducted at the outset of this project identified risks related to computer usage; eyes strain, back pain and electrical hazards. No amendments to the original risk assessment were required, and the recommendations followed.

13 Acknowledgements

This work owes a great deal to Prof. John Clarkson, RAE Prof. Tony Purnell, and Peter Wright (FIA) who produced a constant flow of ideas and guidance through its progression, as well as for the multiple reviews. Thanks are given to Adam Sharpe, and my parents for their time in reviewing it. Simulation work in RaceSim was greatly helped by the time of Steffen Kosuch (of DATAS) and Ruth Buscombe.

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A RaceSim

RaceSim is a simulator package for measuring the performance of cars over a single lap. RaceSim defines the car through a number of different parameters, chassis, power-train, suspension kinematics etc. The Pacejka model is used for simulating tyre dynamics. RaceSim uses a forward time step solver, over a time step accelerating the car before braking to reach a minimum speed. Successfully reaching this minimum speed, the simulation continues accelerating. In a situation where the next section of track cannot be successfully negotiated, the time step is reduced and the previous operation repeated until the track is negotiated correctly. The car proceeds to negotiate the track in this manner, as shown below. [26]