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A Case for Technology – Forcing Transformative Changes in the F1 Power Unit

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Abstract

Formula 1 has always played a major role in technological advancements within the automotive and motorsport sectors. The adaptive changes introduced for the Power Unit (PU) in 2014 forced constructors, in collaboration with industry partners, to invent technologies for exceeding 50% brake thermal efficiency within a short span of time, demonstrating that technology-forcing regulations through motorsport is the favorable route to achieve transformative changes within the automotive sector. Therefore, in an attempt to address arising global warming and health concerns, the present work analytically examines the ambient air quality in track stadia during F1 race events to identify potential PU exhaust emission targets. It models the volume of air contained within the circuits located near heavily built-up areas assuming stagnant air conditions and uniform mixing. The total quantity of exhaust emissions present in the ambient air during the race is estimated using EURO-VI emission standards for different gaseous species and particulate matter. Pollutant concentrations during the race are compared with WHO air quality exposure guidelines in order to identify new emission targets for the next generation F1 PU. Achieving the proposed levels through technology-forcing regulations would underlie fast-paced, ultra clean, Internal Combustion Engine developments applicable to both the motorsport and automotive sectors. A systematic methodology followed for estimating the quantity of air contained within the stadia, total quantity of exhaust emissions from the PUs, targets for transformative changes in exhaust emission levels, and a case for emission targets for Formula 1 PUs are given in this paper.

Introduction

Throughout motor racing history, F1 has shown to be the fastest R&D lab among the industry. With each championship, the urge to win pushes constructors to iterate on existing technologies, within a confined set of technical regulations, achieving technological breakthroughs to develop the most agile, most efficient, competition car. Such innovations are inevitably adopted by the automotive industry due to offering innovative solutions to real-world problems. While this statement stands true for a large number of technological developments, as a result of high industry-scale production cost, the achievable rate of technology transfer between the two sectors is yet to be discovered.

Adopting fuel efficiency as its main focus, the 2014 change in Power Unit (PU) regulations to mild hybrid powertrains, has exhibited that F1 is evolving towards a path most relevant to road cars, demonstrating why now, more than ever, F1 is at the vanguard of technology. Initially developed in 1876 by Nikolaus Otto, the Internal Combustion Engine (ICE) had a brake thermal efficiency of 17% [2]. More than 130 years later, technological developments within the automotive sector resulted modern-day gasoline engines with maximum brake thermal efficiencies falling between 25% and 40% [3]. In just under 36 months, F1's total race fuel and flow restrictions propelled industry partners to develop new combustion technologies incorporating pre-chamber Turbulent Jet Ignition (TJI) in ICEs recording an astonishing 53% brake thermal efficiency and consequently a 18% improvement in fuel consumption [4]. Appealing to high performance automotive manufacturers, the first application of TJI in road cars was demonstrated in 2020 [5]. Not only has F1's regulation changes achieved highly efficient combustion engines in a remarkably short span of time, but the adaptive regulation changes have also made considerable contributions to Electric Vehicle (EV) technology. Previously weighing in excess of 100 kg and achieving just over 39% efficiency, energy storage systems have been improved and are now capable of achieving an efficiency of 96% weighing just over 20 kg with twice the energy density [6]. These, alongside many other, breakthroughs demonstrate why F1 is currently at the forefront of today's automotive development. Through technology transfer, transformative concepts devised to improve performance for racing applications can be utilized for cleaner, more efficient, and more reliable road cars.

Over the years, issues such as global warming and multiple arising health hazards have established European Council Directive initiation of successive stringent emissions legislations on automotive manufacturers [7] (Table 1). Although there have been notable amendments, they are not applicable to track-only vehicles and exclude the motorsport industry. Increasing concerns regarding emissions in motorsport has constructively compelled F1 to adopt an integrated plan, announced late November 2019, to go "net-zero carbon" by 2030 [1]. The initiative entails mitigations such as low-carbon logistics and travel, synthetic fuels, CO_2 sequestration programs, renewably powered offices and factories, sustainable materials, waste recycling, and incentives offering spectators greener ways to reach race events, however, race-specific emission levels from constructors' vehicles still remain unaccounted for.

Gradually, it is becoming rather apparent that arising environmental concerns, if not addressed and mitigated quickly and appropriately, present huge uncertainties with regards to the future of powertrain technology.

Table 1. European Council Directive Amendments to Permissible Emission Levels for the Common Market (1970 – 2014)

Year	Event
1970	70/220/EEC: Initiation of measures taken against air pollution. All Member States required to comply with laid down permissible levels of CO and HCs. Newly manufactured vehicles must obtain EEC-type approval certificates declaring conformity. [8]
1977	77/102/EEC: Amendment issued setting permissible levels for NO$_x$ emissions [9]
1978	78/665/EEC: Developments made in engine design forced an evaluation of previous limits and envisioned further reduction possibility. [10]
1988	88/76/EEC: Amendment adapting approval procedure to be representative of other driving conditions as opposed to just urban traffic conditions. [11]
1989	89/458/EEC: Amendment issued recognizing the impact of CO$_2$ and accordingly adding permissible levels. Recommendation of further test driving conditions to be implemented representing extra-urban conditions. [12]
1991	91/441/EEC: Stricter permissible emission limits. All member states advised to implement various transport concepts in the search for greener powertrain. [13]
1992	Introduction of EURO-I Standard instructing compulsory fitting of catalytic converters in an attempt to further decrease CO emissions. Widespread use of Exhaust Gas Recirculation (EGR) techniques for meeting the newly introduced standard. [14]
1994	94/12/EEC: Advocation of further restraining of CO$_2$ limits in line with reduction of fuel consumption aligned with the outcomes of the UNFCCC. [15]
1996	EURO-II Standard: Different thresholds for petrol and diesel vehicles, lower permissible CO, unburned HC and NO$_x$ emission limits. [16]
1998	98/69/EC: Recognition to the major, previously unaccounted for, pollution contributions of obsolete vehicles. Amendment advised a holistic evaluation of lifecycles and promoted rapid replacement of current vehicles with ones having lower overall environmental impacts. [17]
2000	EURO-III Standard: Modification to test procedure eliminating period of engine warm up. Lower permissible limits for CO and Diesel Particulate Matter (DPM) emissions. Introduction of separate HC and NO$_x$ limits for petrol vehicles. [18]
2009	EURO-V Standard: Further reduction of Particulate Matter emissions from diesel vehicles. All Euro V vehicles are not to be fitted with DPFs to meet new legislative requirements. Tightening of NO$_x$ permissible limits. Applicable to GDI engines only, permissible limits for PM emissions were introduced for petrol vehicles. In an attempt to address the arising concern of fine particulates, particle number permissible limit added alongside existing particle mass limit for diesel vehicles. [14]
2014	Euro VI Standard: Introduced as a consequence of further evidence of urban air pollution resulting various health risks. Included a 67% reduction of permissible NO$_x$ emission limits from diesel engines. Similar emission standards established for both diesel and petrol vehicles. Mandatory use of Exhaust Gas Recirculation (EGR) and DPFs for diesel cars. Selective Catalytic Reduction (SCR) concepts to mitigate high levels of NO$_x$ emissions. [14]

Emissions generated by internal combustion engines can be grouped into four main categories for the purpose of this study. They are Polycyclic Aromatic Hydrocarbons (PAHs), Carbon Monoxide (CO), NOx and Particulate matter content. PAHs, otherwise known as Polynuclear Aromatic Hydrocarbons, is a generic term given to a wide range of substances. It refers to chemical compounds with molecules comprising of only hydrogen and carbon atoms structured aromatically. Physio-chemically characterized as considerably volatile, PAHs are highly mobile and can be redistributed between air and other bodies, including soil and water. If inhaled, experimental studies have demonstrated that, some airborne PAHs cause lung cancer alongside other respiratory health problems. This has brought them to the attention of WHO with particular focus to substances with highest carcinogenic experimental evidence.

Legislative bodies regulate Hydrocarbons either by using Total Hydrocarbons (THCs) or Non-Methane Hydrocarbons (NMHCs) limits. Referred to the C$_2$-C$_4$ series of atmospheric gases, Non-Methane Hydrocarbons (NMHCs) play a major role in the fight for environmental sustainability and climate change. EURO-VI standards dictate a firm 0.068 grams/km of NMHC emissions compared to 0.1 grams/km HC emissions.

Produced as a result of partial oxidation, Carbon Monoxide (CO) is an odorless, toxic, air pollutant. It is the product of incomplete combustion in carbon-based fuel vehicles. High atmospheric concentration of CO leads to lower O$_2$ transport and has multiple concerning health effects including chest pains, dizziness, fatigue, headaches, in addition to various respiratory problems and heart diseases for vulnerable individuals. This has alarmingly led legislative organizations to set a firm limit on vehicle emissions, with the introduction of emission controls in the 1970s achieving an overall 57% reduction by 2001 (Table 1).

NO$_x$ denotes oxides of nitrogen contributing to air pollution specifically Nitrogen Dioxide (NO$_2$) and Nitric Oxide (NO). They are produced as a product of Nitrogen-Oxygen reaction during high-temperature hydrocarbon-based combustion. Significant levels of NO$_x$ contribute to smog formation and acid rain, in addition to the long-term effect they inflict on the tropospheric ozone. In light of this, health and environmental concerns have propelled legislative governments to dictate a constraint 0.06 grams/km on automotive manufacturers (Table 2) in compliance with 24-hour mean advised exposure limits of 40 µg/m^3 set by the European Commission (Table 3).

Particulate Matter (PM) is a representative term of liquid and solid particles originating from combustion. PM has one of the lowest tolerable limits across legislative emissions standards following 1-Hour exposure guidelines of 25 µg/m^3 for PM2.5 fine particulates and 50 µg/m^3 for larger PM10s (Table 3). It is known that vehicle emission levels for automotive applications are set based on the ambient air quality since the area of its use is clearly defined. However, racing engines are not in regular use on day-to-day commuting roads therefore, setting-up emission targets for racing application can be challenging and as a result is not clearly outlined. This warrants a guideline for initiating emission measures and restraints for racing vehicles. If the total amount of pollutants emitted from the race vehicle during race events is estimated it will enable us to define the acceptable tailpipe-out emission levels from high performance engines based on ambient air quality requirements in the stadia during the race. Achieving the targets through technology-forcing regulations would underlie fast-paced, ultra clean, ICE developments applicable to both the motorsport and automotive sectors. Hence, the scope of this pilot study.

Approach & Assumptions

This study assumes the best-case scenario for estimating the total amount of pollutants contained in track stadia during F1 race events. The total distance travelled by the vehicle and the number of vehicles present during the races are known [19] and therefore, the total emission in kg per race can be estimated once a representative emission levels model in g/km is considered. One of the best-case scenarios is to consider EURO-VI emission levels from the vehicle. It can be expected that the actual emission levels from race vehicles will be greater than EURO-VI emission levels, since they operate at high break mean effective pressure levels and therefore, at elevated peak cylinder pressure and temperature conditions. At very high in-cylinder gas temperature the rate of formation of NOx due to Arrhenius type reactions will be significantly higher than that of automotive applications, however, the duration of combustion will be shorter when compared low speed automotive applications. Similarly, at elevated gas temperature CO levels also will be higher due to dissociation process. In addition to this, race engines do not have any after-treatment systems therefore, unburned fuels escaped from the cylinder will also be present in the exhaust. As a result, it can be expected that the tailpipe-out emission levels from a race engine will be significantly higher than EURO-VI emission levels. This study assumes a best case scenario and estimates the total amount of pollutants emitted during race events based on EURO-VI emission levels, hence, the results form an under prediction of the quantity of total emissions rather than an over prediction.

Table 2. Euro VI Emission Standards, Cars and Light Trucks [14]

	g/km			
Standard	CO	HC	NOx	PM
Euro VI	1	0.10	0.06	0.005

Table 3. WHO concentration exposure guidelines for different pollutants. Air Quality Standards [20][21]

	ug/m^3					
	PM10	**PM2.5**	**NOx**	**NMHCs**	**PAHs**	**CO**
1-Hour	50	25	200	20	30	30000
24-Hour	20	10	40	N/A	5	10000

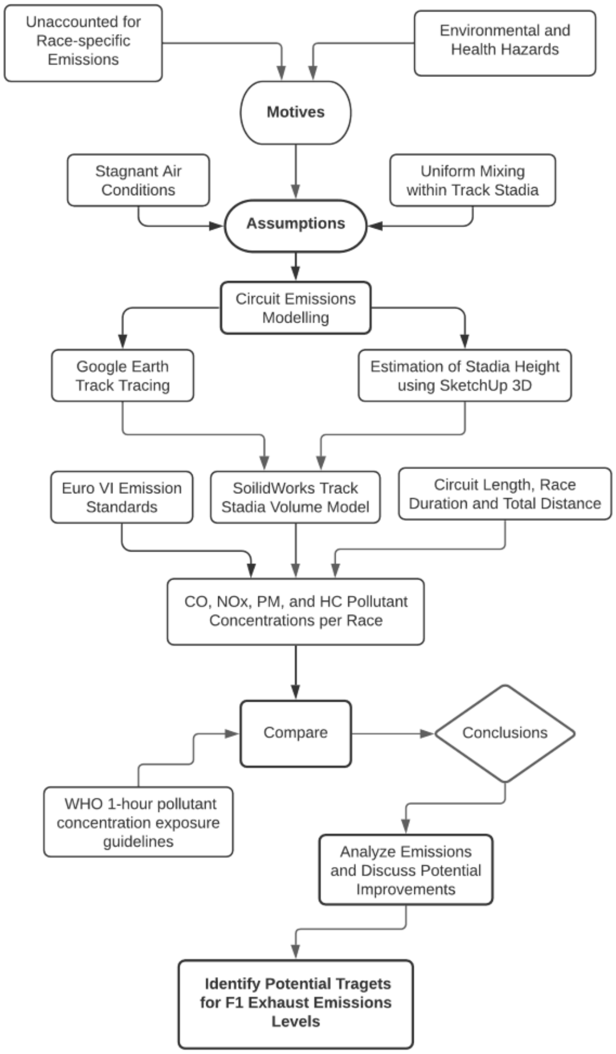


Figure 1. Case Study Workflow diagram

The second assumption considered for this study is uniform mixing of pollutants in the stadia during the race based on total pollutants and lumped parameter approach. The emission levels in g/km corresponding to EURO-VI used for estimating the total amount of pollutants are given in Table 2. This considers CO, THC, NOx, and PM in g/km. The exposure guidelines of WHO used in this study are shown in Table 3. One of the viable approaches for developing emission levels for race engines is to identify the tailpipe-out emission levels required from race engines for meeting WHO exposure limits during race events. Therefore, this study uses the WHO guidelines for threshold settings. The scheme followed for estimating emissions and comparing with the threshold are schematically shown in Figure 1.

Results

3-D Stadia Volume Modelling

Following the systematic procedure scheme shown in Figure 1, an appropriate evaluation of three-dimensional track atmospheric chemistry was conducted. Two-dimensional track measurements were gathered from Google Earth, while SketchUp 3D was used to validate stadia heights due to offering a much more user-friendly way of estimating three-dimensional features. Utilizing 3-D CAD modelling software, SolidWorks, an appropriate real-size track model was generated, from which exact track volume figures can be extracted. The circuit was divided into several sectors to evaluate real-size stadia volumes. Furthermore, mainly due to stadia heights varying at different points around track peripheries, an average height was calculated for each circuit and applied to its respective final 3-D model. This was done to avoid complexity and extensive modelling durations at a minor cost of final model fidelity (Table 4).

The total distance travelled per car for track and the total number of vehicles on the track is taken from [19] for estimating total amount of pollutants in each stadium. The total amount of CO, THC and NOx and PM 2.5 emitted by the vehicle during the race are shown in Figures 4 to 7.

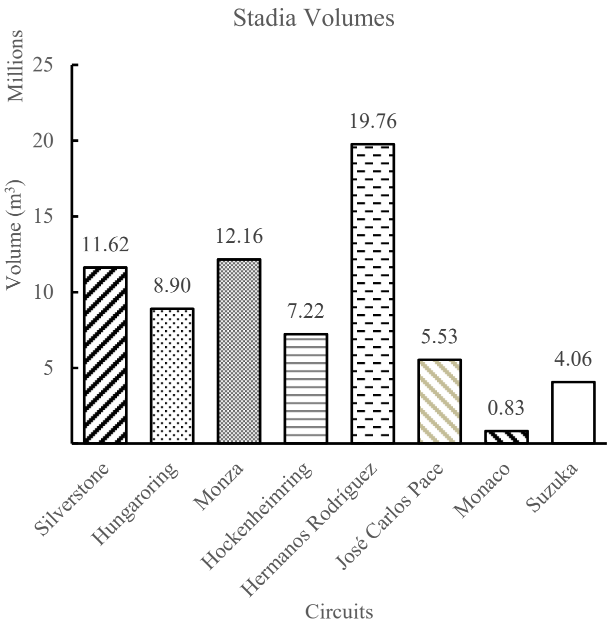
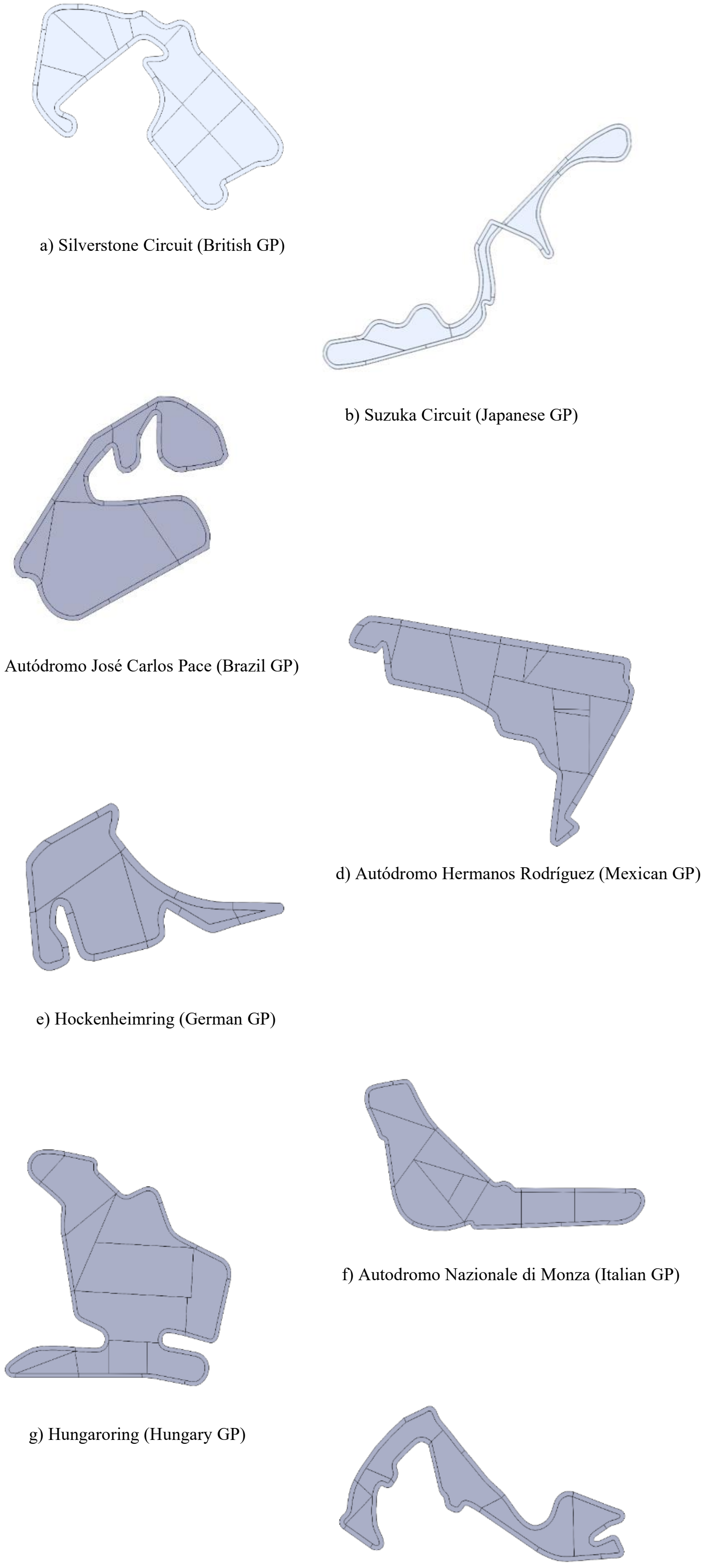


Figure 2. GP Circuits Approximated Stadia Volumes



a) Silverstone Circuit (British GP)

b) Suzuka Circuit (Japanese GP)

c) Autódromo José Carlos Pace (Brazil GP)

d) Autódromo Hermanos Rodríguez (Mexican GP)

e) Hockenheimring (German GP)

f) Autodromo Nazionale di Monza (Italian GP)

g) Hungaroring (Hungary GP)

h) Circuit de Monaco (Monaco GP)

Figure 3. Track Stadia 3-D Volume Models

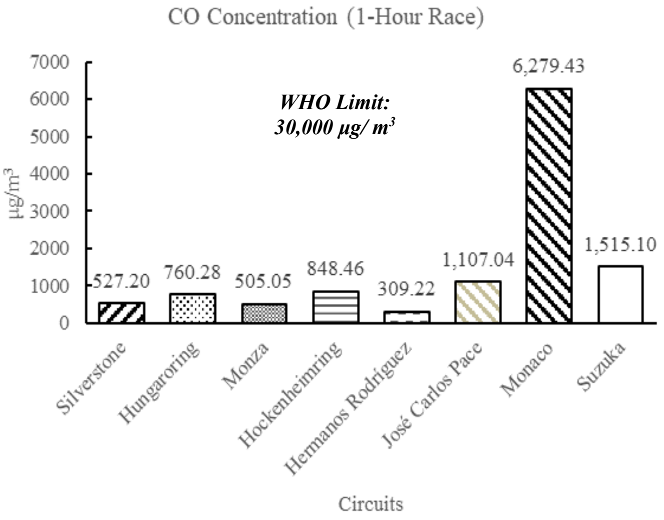


Figure 4. GP Circuits – Race specific CO Pollutant Concentration

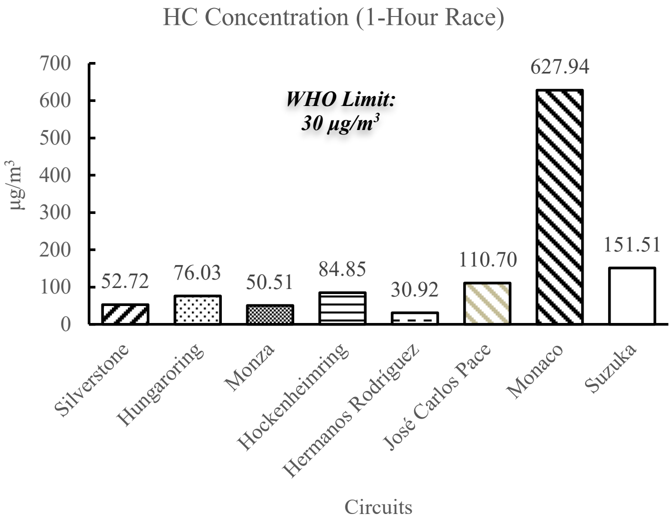


Figure 5. GP Circuits – Race specific HC Pollutant Concentration

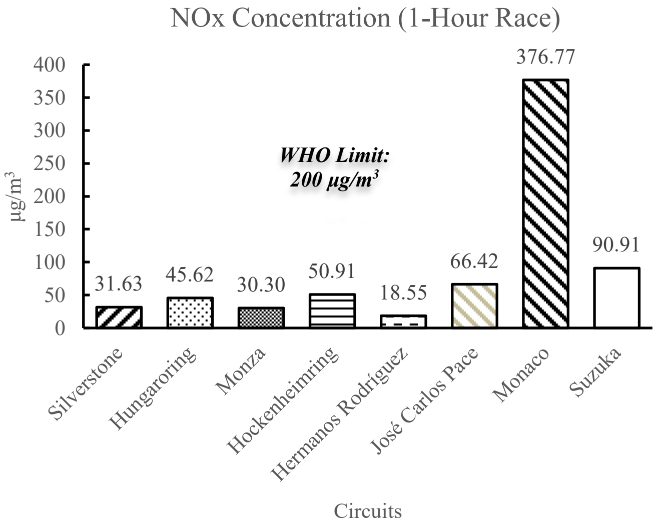


Figure 6. GP Circuits – Race specific NOx Pollutant Concentration

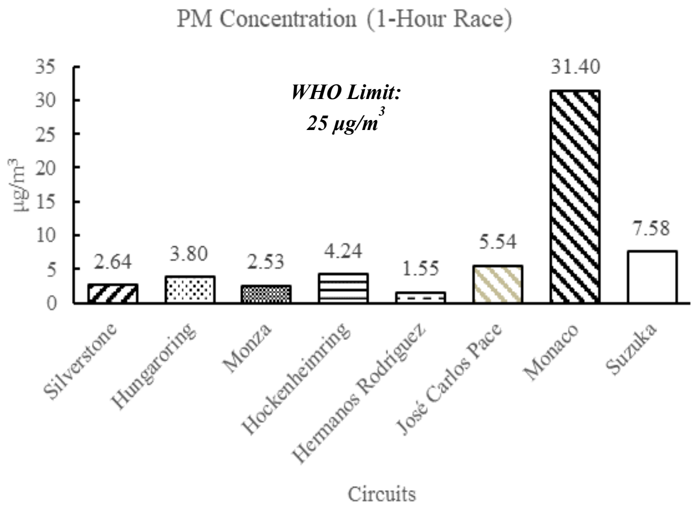


Figure 7. GP Circuits – Race specific PM Pollutant Concentration

Table 4. Example – Averaging Stadia Heights, Volume Modelling Error

Circuit	Silverstone	Hungaroring
Track Stadium Volume – Average (m^3)	11,621,199.93	8,895,967.78
Track Stadium Volume – Exact (m^3)	11,348,866.63	9,212,269.45
Percentage Error (%)	**2.34%**	**3.56%**

Analysis

Analyzing the Grand Prix, total race distance is determined through multiplying the respective number of laps by circuit length. This concludes an overall distance covered by each participating constructor vehicle. The total number of race kms is then determined for all 20 vehicles. Subsequently, EURO-VI emission standards (g/km) are used to give an approximation of overall race-specific emissions. Circuit pollutant concentration volume output in $\mu g/m^3$ is estimated and compared with WHO exposure limits. Evaluation of the 3-D stadia models (Figures 3) produced a numerical representation of individual stadia volumes as shown in Figure 2. Its rather apparent that stadium volume is governed by the circuit's circumferential peripheries. This is reflected in the significantly lower volume of Circuit de Monaco (Figure 3h), a city track, as a result of less overall area covered between track boundaries.

CO pollutant concentrations, shown in Figure 4, compared with 1-hour WHO limit of 30000 $\mu g/m^3$ highlights that race-specific emission levels are below the WHO limit; if the tailpipe-out CO levels are equivalent to EURO-VI levels and the pollutants are contained within the stadium. Moreover, Figure 5 illustrates PAH concentration at different track stadia during Grand Prix events. Analysis showed data points peaking at 627.94 $\mu g/m^3$ at Circuit de Monaco with a low of 30.92 $\mu g/m^3$ at Autodromo Hermanos Rodriguez in Mexico exceeding the WHO and European Commission advised concentration of 30 $\mu g/m^3$ for all stadia. Comparatively, Figure 6 shows results of estimated NO_x concentrations at each of the eight different circuits. While demonstrating data points reasonably below the 1-hour 200 $\mu g/m^3$ WHO threshold for most circuits, Circuit de Monaco exceeds the limit averaging 376.77 $\mu g/m^3$. Similar trends are observed at the circuit for particulate matter, PM2.5, (Figure 7) demonstrating 31.40 $\mu g/m^3$ surpassing the hourly WHO advised limit of 25 $\mu g/m^3$. As anticipated, a strongly inverse correlation exists between track stadia volume and pollutant concentrations. Calculated approximations analyzed on a Fail/Pass basis showed failure to comply with at least one hourly pollutant exposure limit for all circuits. Despite exceeding WHO guidelines, most of the estimated concentration data points for each of the pollutants fall close to each other. Being a significantly lower volume stadium, Circuit de Monaco, demonstrated highest levels of all analyzed emissions. The circuit exhibited excessive levels of pollutants exceeding WHO limits, placing the stadium of Circuit de Monaco amongst which warrant significant reduction levels in tailpipe-out emission to meet WHO threshold.

Proposed F1 Emission Targets

Outlined in Figures 8, 9, 10, and 11 are the respective proposed total weighting targets to EURO-VI classified emissions to meet the WHO exposure threshold (Table 5). It is demonstrated that given EURO-VI emission levels, ambient air quality meets the advised limits for all emission species with the exception of THCs. This suggests that further restriction beyond the existing EURO-VI 0.1 g/km THC standard is required if the WHO threshold is to be met at current race events. Meeting such limits for high BMEP racing engines at wide open throttle offers a wide scope of innovation in the areas of combustion control, emissions control, and after-treatment. As a baseline for technological targets, levels should be set-up such that lower volume circuits nearest to heavily built-up areas are compliant.

Table 5. Proposed F1 Emission Targets (grams/race)

Circuit	**CO** (grams/race)	**THC** (grams/race)	**NOx** (grams/race)	**PM** (grams/race)
Silverstone	2,905	348	2,324	116
Hungaroring	2,223	266	1,779	88
Monza	3,035	364	2,431	121
Hockenheimring	1,805	246	1,444	72
Hermanos Rodriguez	4,941	592	3,952	197
Jose Carlos Pace	1,381	165	1,105	55
Monaco	**207**	**24**	**165**	**8**
Suzuka	1,015	121	812	40

Limitations

Adopting an air mass balance model, a study evaluating circuit volume race-specific emissions was conducted. While estimated for A best case scenario, it stimulates realistic estimations of measured pollutant concentrations in track stadia. The method unveils an improvement on existing techniques, it does not account for emission Source Proximity Effect (SPE) neglecting variability of concentrations and assuming a unified average. However, this pilot study provides a method for quantifying the effect of race on air pollution levels in the stadia based on the best-case scenario. A more realistic worst scenario study can be conducted using this approach for developing technology-forcing regulations for cleaner and greener motorsport using internal-combustion engines.

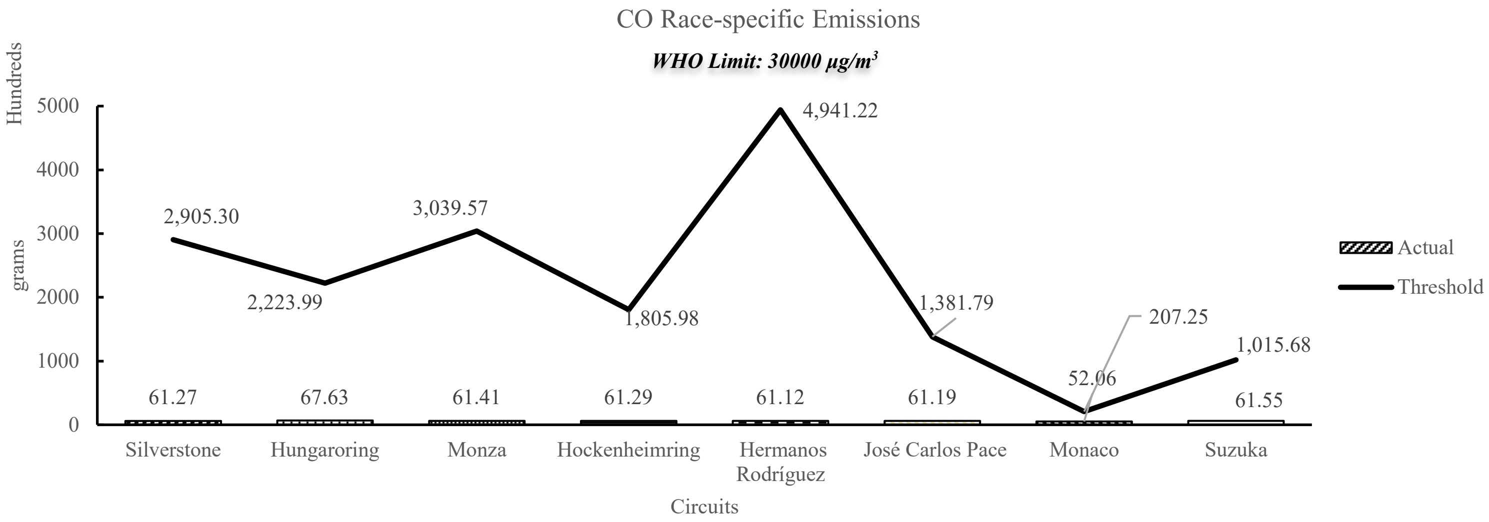


Figure 8. CO Race-specific Emissions in comparison with WHO Threshold

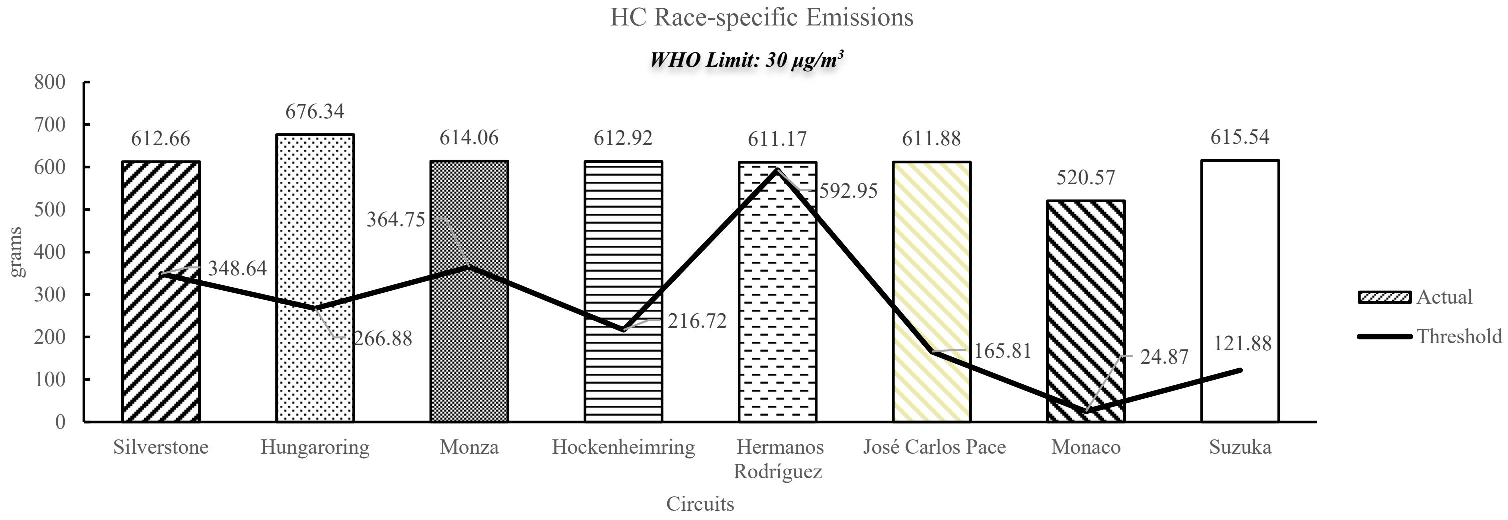


Figure 9. HC Race-specific Emissions in comparison with WHO Threshold

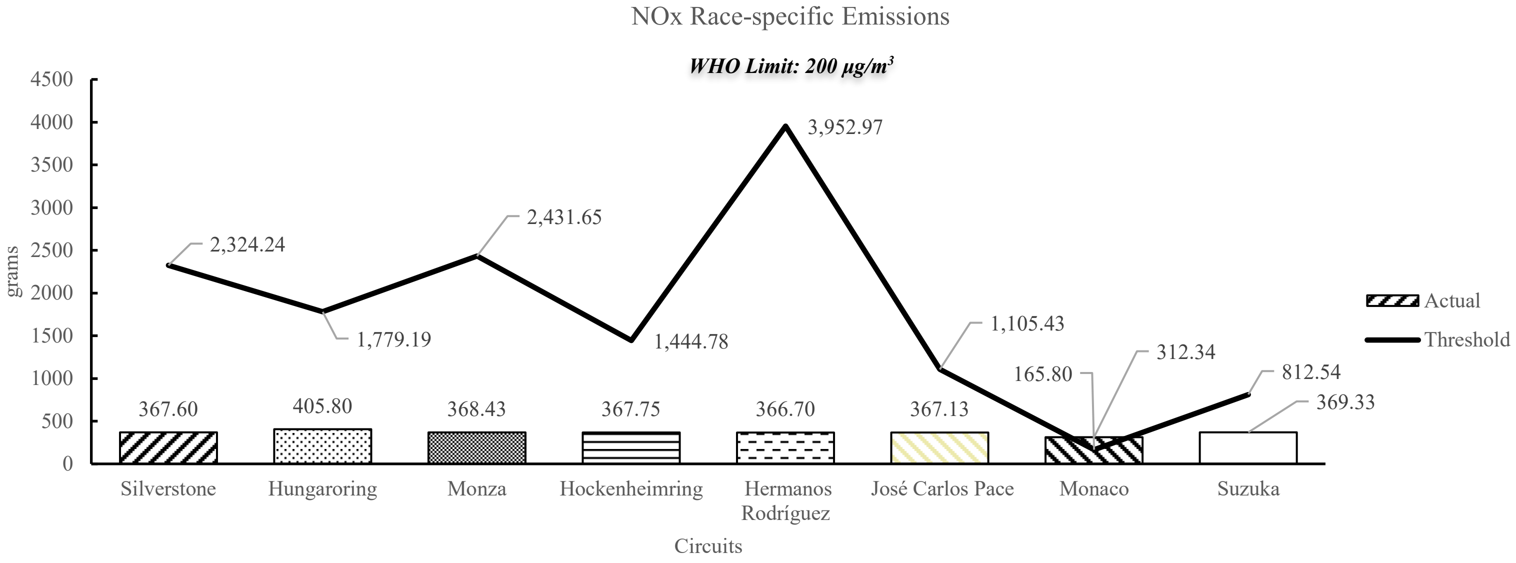


Figure 10. NOx Race-specific Emissions in comparison with WHO Threshold

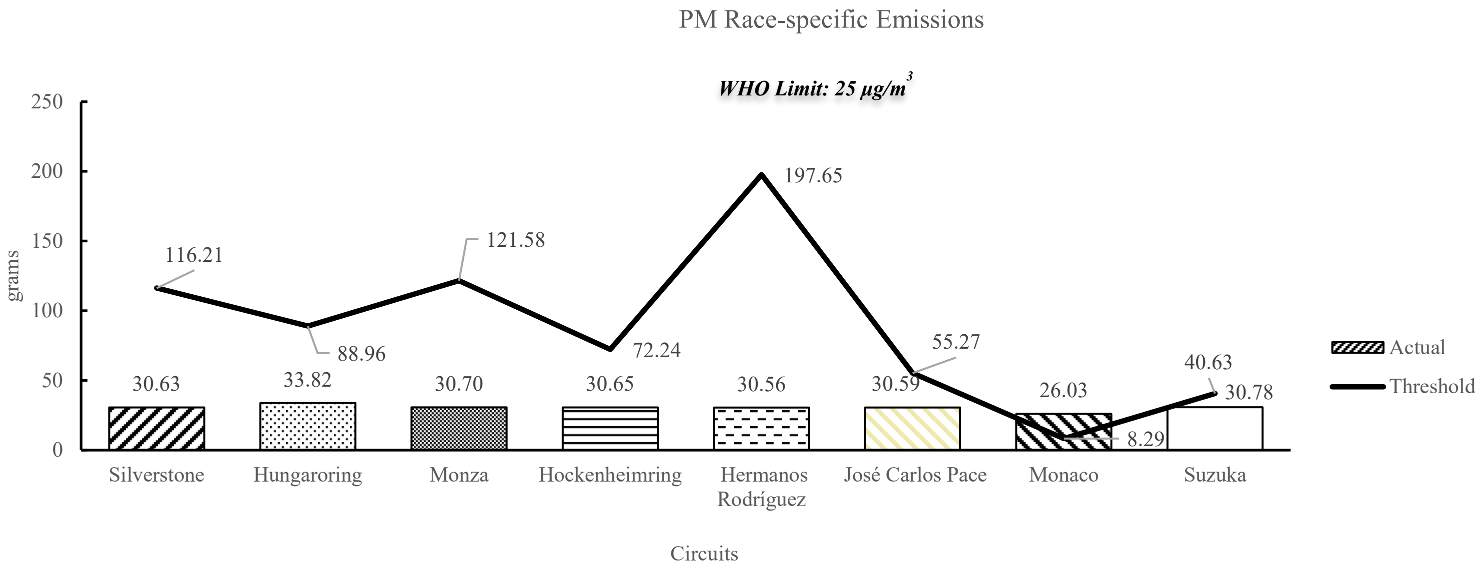


Figure 11. PM Race-specific Emissions in comparison with WHO Threshold

Conclusions

While it is of no doubt that engine duty cycles differ between road and racing motor vehicles, presently implemented technical regulations in F1 is on the way to achieve fuel efficient internal combustion engines. Based on a best-case scenario, this study illustrated that pollutant levels within track stadia at F1 race events can be modelled using simple tools to quantify effects on the ambient air quality. Adopting an air mass balance model and assuming EURO-VI emission levels, analysis demonstrated that 3-Dimensionally modelled race-specific emissions fall within specific WHO exposure guidelines with the exception of THCs. Furthermore, being a narrow city track, Circuit de Monaco demonstrated extravagance levels of NOx, THC and PM emissions, all of which significantly exceeding the WHO threshold. At wide open throttle, the technology required for meeting EURO-VI emission levels in motorsport, given high engine operating speeds and BMEP, if introduced in Formula 1 would have an instantaneous revolutionary impact on the automotive industry meeting near zero emission levels and sustaining clean air in built-up areas.

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