Software analysis of racing drivers' interfaces using Link Analysis and Fitts' Law

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ABSTRACT

This paper discusses the development, application, and proof-of-concept test of software designed to analyse specific aspects relating to the usability of steering wheel-based interfaces in racing cars. A combination of link analysis and Fitts' Law is employed in order to identify interface efficiency and potential driver physical workload. The racing driver's primary goal is to win races, this is achieved through a combination of primary and secondary tasks. These sometimes-complex secondary tasks can however overload the driver and cause distraction, leading to driving errors with potentially serious consequences. Equally, drivers experiencing high primary task workload may be more prone to making interface-based errors, particularly when complex secondary tasks are performed. Steering wheel-based interfaces were analysed from four 2017 Formula One season cars, measurements were taken, and control coordinates, dimensions, and control types recorded. A set of typical secondary interactions involving interface controls common to all the cars that might take place within the first ten laps of a race were derived from on-board footage. A software application was developed to load this control layout and interaction data, and carry out link analysis, Fitts' Law and hybrid calculations. The analysis revealed a range of data, including traversal distances and indices of difficulty for activating individual controls or combinations. This provides insight into efficiency and physical workload levels associated with interface designs. Designs can then by optimised and retested by updating the control layout data, or with variations of interaction data, with the ultimate goal of reducing errors as well as improving safety and driver performance.

KEYWORDS

Link Analysis, Fitts' Law, Motorsport, Usability

Introduction

Modern F1 car user interfaces are considerably complex (Gkikas, 2011). The nature of motorsport is time-critical and drivers are faced with a high cognitive workload primary task and little time and resources for secondary tasks (Baldisserri et al., 2014). By analysing the interactions a driver makes with the controls mounted on the front of the steering wheel using Fitts' law and link analysis, data can be obtained that reveals potential areas for improvement. These might be able to reduce the time required for drivers to operate their controls, reducing distraction and possible driver error (Young, Lee and Regan, 2008).

Application Development

Control layout data was derived from four 2017 season F1 team's steering wheels, a fairly diverse selection of designs was selected from McLaren, Ferrari, Mercedes Benz and Red Bull as used by Alonso, Vettel, Hamilton and Ricciardo, all right-handed drivers. Due to the competitive nature of the sport, precise data on dimensions is not readily available. However, the central LCD display common to all wheels, the PCU-8D, manufactured by McLaren, is commercially available and its dimensions are within the public domain. Images of the four steering wheels were sourced where they were photographed squarely from the front view. Since the LCD dimensions were known, this allowed the wheel and control dimensions to be extrapolated to within approximately ±2mm by printing the images in a 1:1 scale and measuring them. This was considered acceptable for a pilot study as the margin for error is unlikely to affect the fundamental results on a macroscopic level. Control types were classified, together with their coordinates from a top-left origin. The control type also determines the type of interaction required, for example, buttons are pressed, but rotary controls require rotation. This data was saved in the form of a comma separated value file (CSV) with the extension '.CON' for 'control'.

Table 1. Example control data file contents (Mercedes)

Control	X Coord	Y Coord	Control Type	Size (X)	Size (Y)	Functionality
LRest	55	65	LRest	10	10	Left thumb rest position
RRest	226	65	RRest	10	10	Right thumb rest position
MF10	73	76	Button	10	10	Selection change of 10 items
Radio	212	32	Button	10	10	Speak to engineers via radio
OV	37	19	Button	10	10	Overtake button
Ack	213	116	Button	10	10	Acknowledge
Neutral	69	32	Button	10	10	Neutral
Limiter	185	96	Button	10	10	Pitlane limiter
BB+	227	24	Button	10	10	Brake Bias/Balance forward
BB-	54	24	Button	10	10	Brake Bias/Balance backwards
MF1	208	76	Button	10	10	Selection change of 1 item
Multi	138	112	Rotary	22	22	Multiple function control
Tyre	138	112	Rotary	22	22	Select tyre settings
Fuel	174	115	Rotary	22	22	Select the fuel mixture/power
Diff+	223	83	ThumbWheel	8	18	Differential / adjusts handling
Diff-	223	83	ThumbWheel	8	18	Differential / adjusts handling
SOC	102	115	ThumbWheel	22	22	State of electrical charging

In Table 1, Rest positions (LRest, RRest) represent the approximate locations of the driver's thumbs when the steering wheel is being held naturally. The shaded section of Table 1 highlights the control set that was common across all four cars. Controls from this common set featured in the interactions set that defined the actions of the driver. Other controls do exist on the wheel and were included on the .CON file, but were excluded from the set used for interactions due to non-commonality or doubt over functionality. A notable exclusion is the DRS (Drag Reduction System) control, this is common to all 2017 F1 cars and frequently activated. The rationale for exclusion was the Red Bull and McLaren steering wheels mounting this control on the back of their wheels, preventing an accurate comparison.

A test set of common control activations was derived from footage of various teams at different stages of races. This allowed a generic set of interactions to be generated that represented potential usage within the first ten laps of a race. It included 155 separate interactions involving the driver preparing the car on the grid, the initial laps, a loss of control, a yellow flag incident and a pit-stop. Interaction data included the lap number, distance from the start/finish, stage of the race, control activated, race stage, and any associated note. A map of the Monza grand prix circuit in Italy was measured to reveal the distances of corner starts and exits. In most cases, drivers utilise their steering wheel-based controls on straights, this data revealed the distance parameters within which controls are likely to be activated at Monza. The interaction data was saved in CSV format with the file extension '.INT' for 'interactions'. The controls and interactions files could then be loaded into the application for analysis.

Table 2. Example section of interaction data

Lap Number	Distance from start (m)	Control Activated	Stage of race
7	3150	Radio	1
7	4000	Multi	1
7	4200	MF1	1
7	4220	MF1	1
7	4400	Ack	1
7	4700	BB+	1
8	200	SOC	1

The interaction data required additional processing as it only included one dimension of drivers' interactions; when they reach for and activate their controls. The additional second dimension of interactivity data; the return from the control location to the drivers' 'rest' position was generated algorithmically. It is likely that if two interactions are temporally and dimensionally close, that the driver's hand will not return to the rest position and will simply traverse to the next control activation, this assumption was based on this behaviour being witnessed in video footage. A customizable variable was provided to specify the minimum on-track distance between control activations below which a driver will not return their hand to the rest position. For the pilot study, this was set to an estimated value of 100m (This equates to approximately 1s at the average speed at Monza). The size of the 'rest' positions for all four steering wheels was defined with a fixed value of 10mm x 10mm. This constant value was only used for the pilot study, future studies would use the area of the thumb aperture unique to each wheel.

Link Analysis

The processed interaction data, including algorithmically generated 'rests' was combined with the control layout data to generate a pictorial representation of the drivers' controls and overlay the links between them, resulting in a graphical link analysis (Fig.1). This software also constructed traditional graphical matrices illustrating the links and their frequency (Stanton et al., 2014). Link analyses were bi-lateral, allowing separate analyses of left and right hands in order to provide data into the interactions split. Options were built into the application to consider controls that were centrally placed or required removal from the steering wheel to operate. One option assumed that all controls that required hand-removal were operated by the driver's dominant hand. A second option assumed that hand-off controls were operated by the closest hand, with central controls operated by the dominant hand. The 'handedness' of drivers could be specified as a separate variable. The data presented assumed a right-handed driver using their dominant hand to activate controls that require a hand to be removed from the wheel. The application was designed to output a set of statistics for both hands based on the link analysis, the results can be seen in Table 3.

Fitts' Law

The index of difficulty (ID) was calculated using Fitts' original equation, based on Shannon's logarithm (MacKenzie, 1992):

$$ID = log_2(\frac{2A}{W})$$

where A represents the traversal distance and W is the width of the control. Traditionally, W would be measured across the axis of motion (AoM), however, as some of the controls are not circular, this value could vary based upon AoM. For the purposes of this pilot study, W was always represented by the width, even in the case of rectangular controls. Values for traversal distances were simply calculated using Pythagoras, the interactions file and calculated rest positions denoted start and end positions, these were cross referenced with the controls file, thus providing the start and end coordinates. The Fitts' law analysis revealed a range of bi-lateral statistics on index of difficulty. Results are shown in Fig.3 and Table 3.

Results

The pictorial output from the link analysis provides insight into the driver's traversals to-and-from controls and rest positions. Left-hand traversals are shown in red and right-hand traversals in green. Buttons are illustrated as red (light grey) circles, thumbwheels as green rectangles, rotaries in blue (dark grey), rest positions as grey squares, and toggles (McLaren only) in yellow (v. light grey).

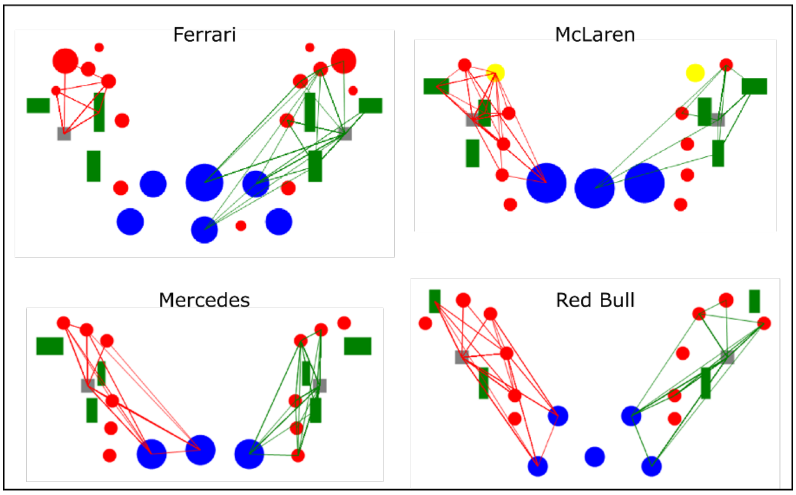


Figure 1. Link analysis output generated by the software representing controls mounted on the front of the steering wheels.

Examining the graphical link analysis in Fig.1, the Ferrari wheel indicates a high physical workload by the driver's right hand, compared to the left, both in terms of number of interactions, and length of traversals. The McLaren wheel appears to require the driver's left hand to carry out a higher number of traversals, however, the right hand is required traverse the furthest individual distances.

The Mercedes wheel generates a higher number of interactions for the driver's right hand, but requires longer individual traversal distances from the left. The Red Bull wheel appears to require a similar number of interactions by both hands.

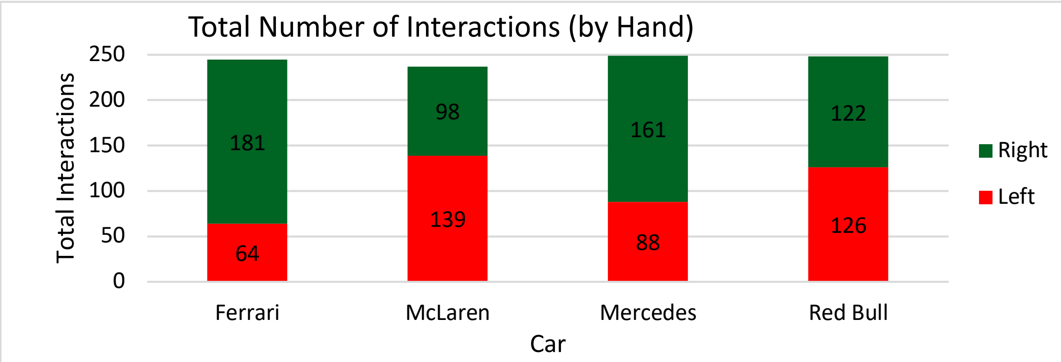
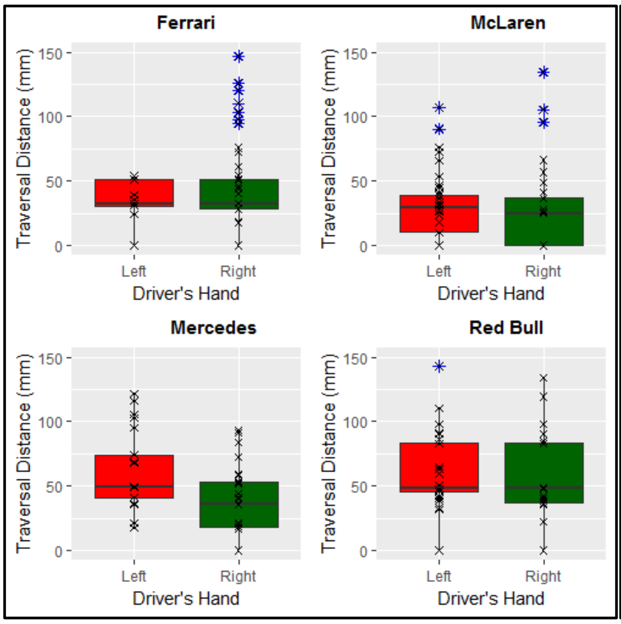


Figure 2. Interactions split by hand.

Examining the number of interactions that each hand has to carry out in Fig. 2, as was evident from Fig.1, the Ferrari wheel requires the driver's right hand to carry out the majority of interactions. The Mercedes wheel is less biased to the driver's right hand, the McLaren is biased toward the driver's left hand, and the Red Bull is fairly equal bi-laterally. Although there were 155 unique interactions in the interactions file, the total number is higher due to the additional 'return to rest position' interactions that were algorithmically generated. Fig. 3 further illustrates the bi-lateral traversal distances required using box plots. Ferrari's interquartile ranges, representing the spread of the middle portion of data, are similar, with upper quartile values of around 50mm. Median values are identical at just over 32mm, however there are multiple outliers representing values more than 1.5 times above the upper and below the lower interquartile range bounds. These indicate the requirement for the right hand to traverse large distances for several interactions, the greatest traversal almost reaching 150mm. The McLaren showed low upper quartile values compared to the other wheels of around 40mm, median values were also the lowest recorded at approximately 29mm (left) and 25mm (right). In addition to this, McLaren's lower quartile values were less than the other wheels at approximately 10mm (left) and 0mm (right). There were however multiple outliers for both hands, approximately 100mm (left) and between approximately 100mm (left) and 134mm (right). The Mercedes showed variation in interquartile ranges, the right hand showing lower traversal distances of between approximately 20mm and 55mm, (median 36mm), compared with the left hand, 75mm (max) and 40mm (min), (median 50mm). Both left and right hands exhibited large ranges between upper and lower extremes of approximately 100mm. The Red Bull wheel exhibited the highest upper quartile values of approximately 80mm for both left and right hands. Results indicated that the right hand experienced a high range between upper and lower extreme values, of over 125mm. Median values were also similarly high for both left and right hands at 48mm.



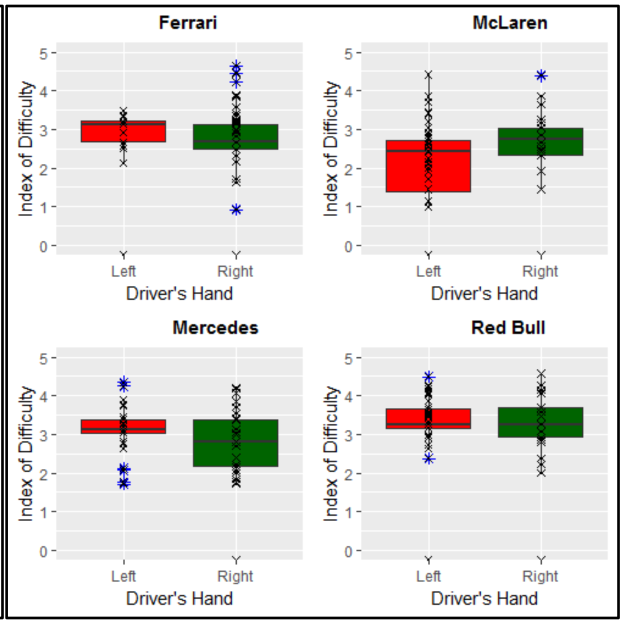


Figure 3. Bi-lateral traversal distances (mm)

Figure 4. Bi-lateral indices of difficulty

Fig. 4 shows the Ferrari wheel's interquartile ranges for ID similar for both left and right hands at between 2.5 and 3.25, the median value for the left hand was higher at 3.1 compared to 2.7 (right). The right hand also showed multiple outliers with ID values varying between approximately 1 and 4.7. The McLaren wheel exhibited a large interquartile range for the left hand, of between approximately 1.4 and 2.7; upper and lower values varied between 1 and 4.5, with a median of 2.4. The right-hand median value was higher at 2.8, however, the interquartile range (2.4 to 3) and overall range (1.5 to 4) were both lower. Results showed a large disparity in ID interquartile ranges between hands for the Mercedes wheel, 3 to 3.4 (left) and 2.2 to 3.4 (right), median values however, were similar at 3.1 (left) and 2.8 (right). Upper and lower values for the left hand ranged between 2.6 and 3.9, whereas the right-hand exhibited values between 1.6 and 4.3. The left hand did show multiple outliers between 1.6 and 4.4. The data on the Red Bull wheel revealed identical median IDs of 3.3, and similar interquartile ranges, both within the bounds of 2.9 to 3.7. The driver's right hand experienced a slightly larger overall range of ID (2 to 4.5) compared with the left (2.6 to 4.4).

Table 3 shows the collated results for all four steering wheels. This includes total distance traversed for each wheel. The Red Bull wheel required the driver to traverse the furthest between controls and rest positions over the 10-lap interaction set, a total distance of 13.5m was covered. The Mercedes driver would have traversed 10.8m, the Ferrari driver 10m and the McLaren driver 7m.

Table 3. Bi-Lateral Traversal distances and Indices of Difficulty for each steering wheel.

	Ferrari		**McLaren**		**Mercedes**		**Red Bull**	
	Left Hand	Right Hand	Left Hand	Right Hand	Left Hand	Right Hand	Left Hand	Right Hand
Mean ID	2.985	2.798	2.267	2.671	3.183	2.764	3.398	3.346
Median ID	3.129	2.678	2.433	2.755	3.110	2.807	3.263	3.263
Min ID	2.126	0.922	1.000	1.453	1.710	1.710	2.379	2.000
Max ID	3.478	4.644	4.420	4.392	4.350	4.217	4.492	4.573
Mean Traversal (mm)	35.50	43.00	33.44	24.59	60.24	34.44	57.82	51.20
Median Traversal (mm)	32.55	32.55	29.20	25.00	49.39	35.84	48.01	48.01
Min Traversal (mm)	0.00	0.00	0.00	0.00	17.72	0.00	0.00	0.000
Max Traversal (mm)	54.00	146.82	107.07	134.41	121.65	93.55	142.88	133.84
Total Distance (mm)	2272.40	7784.13	4648.784	2410.72	5301.53	5546.19	7285.80	6247.25
Combined Dist. (mm)	10056.53		7059.51		10847.72		13533.06	
Interactions Split (155 + generated ‘rest’ returns)	64	181	139	98	88	161	126	122

Discussion

The link analyses reveal the lateral interactions bias, in terms of traversal distances. The Fitts’ Law data provides insight into difficulty of control activation. Examining the results, the McLaren wheel appears to be the most efficient in terms of total distance traversed, and the majority of traversals appear to be fairly short with minimal outliers. The outliers were all interactions with the rotary controls. All four wheels generated the greatest traversals when rotary controls required activation as they are all positioned in the lower central position of the wheels. This is logical as they are traditionally used with low frequency. The Ferrari wheel showed considerable bias towards the driver’s right hand, suggesting either a driver’s preference or a specific design philosophy. The Mercedes biased towards the left hand performing more interactions. On first consideration, it is logical that the dominant hand should be tasked with the majority of the work, and that which is more complex. This is due to increased efficiency and precision that dominant hands often exhibit (Hammond, 2002). However, the criticality of the primary task; controlling the vehicle, coupled with the precision, accuracy and strength requirements (Pruett, 2012), may suggest that secondary control activation interactions should be biased towards the non-dominant hand, freeing the stronger dominant hand for car control (Masmejean, 1999). This could potentially explain the Mercedes design philosophy. The Red Bull wheel appeared to be sub-optimal in terms of traversal distances, and both hands shared almost equal interactions in terms of control activation frequency and traversal distance. This is potentially another design philosophy, to share the load. There does exist the possibility that the Red Bull design is deliberate, spacing controls to prevent accidental activations, and the potential disadvantage of time taken to activate controls is outweighed by the advantage of less incorrect control activations. The results for the Ferrari wheel indicated similar low traversal distances for both hands, however the right hand experienced multiple outliers caused by the activation of rotary controls mounted in the centre of the wheel. The Ferrari design features six of these controls, compared to five for Red Bull and three for McLaren and Mercedes. Although this generates a higher physical workload for the drivers, the rationale might again be to separate the controls used with low frequencies to a less accessible section of the wheel, and optimise the placement of the more frequently used controls by locating them close to the rest positions. Ferrari's use of six rotaries might suggest they place a priority on not only separating rarely and frequently controls, but also separating functionality possibly to aid understandability.

The indices of difficulty (ID's) for secondary control activations highlight the interactions that are potentially more likely to cause distraction to the driver, or might require more time to complete. In terms of optimisation, controls used with high frequency, or those that are of critical importance should exhibit low ID's. Gkikas (2011) suggested control layouts should be defined based upon task types and time taken to operate. There is a balance to be found between control usage frequency and criticality. The results indicated that for the Ferrari, Mercedes and Red Bull wheels, the ID interquartile ranges for both hands varied between 2 and 4, this might be indicative of the levels that are generally aimed at by designers, or tolerated by drivers. Ideally the values that are above the upper quartile should correspond to controls used with lower frequencies, and the outliers do fall into this category. The McLaren wheel appears to be the more highly optimised, with lower ID levels for both hands than the other wheels. The disparity between the McLaren and Mercedes wheels in terms of biasing the ID to the left or right could be due to design philosophy or driver preference. Ferrari and Red Bull appeared to balance the ID across hands, although the Red Bull ID values were high, potentially due to their traversal distances. The high ID total variation for the right hand on the Ferrari wheel was also likely due to the high traversal distances. Gkikas (2011), suggested a primacy-based approach to F1 steering wheel design which groups controls and dictates positioning dependant on frequency of usage. This would likely result in lower traversal distances and IDs, however, critical controls such as the neutral button or pitlane speed limiter may be better placed close to the drivers' rest position despite the low frequency of usage. The risks associated with their being activated too late or not activated at all are potentially high. Observation of current wheel designs reveals that it is common for teams to favour placing these critical controls close to the drivers' rest positions, possibly for this reason. Therefore, controls should ideally be weighted by criticality, as this would allow further calculations to assess control position suitability. This combined with analysis comparing control usage frequency with ID would allow a comprehensive set of control layout optimisations to be identified algorithmically.

Further Work

Results would benefit from 'rest' positions being more accurately depicted as non-regular shapes, with coordinates that reflect the entry point into the 'rest' aperture of the wheel, rather than the 'rest' positions themselves. Further work investigating the most suitable Fitts' Law equation adaptions might lead to improved and more relevant results. The software could conceivably identify the control positions that need optimisation if not only frequency of use was defined, but also criticality. Studies into the speed of movements and time taken to activate the different types of controls could, in conjunction with the traversal distances reveal valuable data on the overall durations of control activations and index of performance. Additional investigations into aspects of rotary control usage, such as time to operate, direction of motion and required torque, taking into account the use of gloves, would likely generate more accurate results. The ability to define control (.CON) and interaction (.INT) files allows fast prototyping of interface designs. This pilot study used a consistent set of interactions to compare four interfaces, but alternatively, the interaction file could be varied to reveal the performance for a given interface design when utilised differently. It would also be entirely possible to make the application generate a large set of scenarios of usage that vary within given ranges. The outputs could then be batch processed to carry out an extensive analysis of an interface design. The possibility that each teams' cars might require different levels of interface interactions should be investigated. For example, a more responsive chassis might require less handling adjustments. This pilot study has revealed the potential benefits of a combining Fitts' law and link analysis in a usability assessment tool. However, the possible improvements that are identified only cover small areas of overall usability; efficiency and speed of usage. Whilst these are important, particularly in the context of motorsport, other aspects such as understandability (Bevan, 2001), user characteristics (Stanton & Baber, 1992) and effectiveness (Shackel, 1991) may preclude the optimal interface design with respect to this analysis.

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