High Acceleration and the Human Body

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1 Introduction

On Sunday April 29th, 2001, CART was to make its debut at the Texas Motor Speedway. Two hours prior to the green flag, the drivers refused to race on the track. While running practice laps the previous two days, drivers were reaching relatively higher than normal speeds (topping at 236.9 mph) on the oval's high 24° banked turns. Drivers were subjected to over 5G on their bodies and of the 25 drivers, 21 of them complained of being disoriented and dizzy while racing. Others complained of visual problems and one driver admitted to momentarily passing out on the back stretch and drifting into the banking. Every driver that completed more than 10 laps had trouble. CART, on behalf of the drivers' complaints and safety concerns, canceled the 250 lap race much to the protest of the track's manager and the anger of 60,000 fans [3].

Figure 1: Fans don't care about G.

It was eventually determined that these symptoms were due to a lack of blood flow to the head and inner-ear imbalances because of the high vertical G-forces on the track caused by the unique banking and the speed capability of the cars. There was clearly a problem here, and attempting to figure out what exactly the problem was became the challenge. Many different types of races are held at Texas Motor Speedway but such complaints and issues had never surfaced before. For the better half of the 20^{th} Century, extensive research in the Air Force has looked at how the human body copes with such external forces, but such factors were never directly thought for concern in terrestrial automotive racing. To investigate just how dangerous high G-forces are involves looking at this vast history of biodynamics and biophysiology, attempting to analyze just what went on in the case of CART at TMS, investigating whether high G-forces should concern 'the average driver', and finally looking at biomechanical concerns and discussing possible solutions that could keep this from happening again.

2 The Standard Acceleration of Gravity (G)

The INDY drivers did not get dizzy from just speed alone that day, but rather a combination of the speed, driver head positions, and most importantly, the external G-forces acting on them.

As terrestrial inhabitants of the Earth, the human body is used to a particular force: gravity. The forces felt as a body accelerates and decelerates can be described in multiples of gravity, or G. A G-force is simply a descriptive measure of acceleration. When stationary, the force felt by Earth's gravity is 1G, however when a body undergoes a change in speed and direction, that force increases in proportion to the rate of change [27].

As drivers race around a corner, a car's engine and aerodynamics provide the forces keeping it attached to the ground as well as pushing the drivers into their seats as a result of the inertia their bodies feel in relation to the accelerating car around the turns. The magnitude of these forces involved can easily exceed the Earth's gravitational force. G-forces can be front-to-back (G_x), side-to-side (G_y), and head-to-toe (G_z). When G_x forces increase, the body is pulled forward or pinned to the seat. G_y forces push the body up against the side of the car (such as when riding a roller-coaster). When an increase in G_z force occurs, the body will feel heavier. The human body can tolerate a great deal of G-loads, however just how many G it can take is a little more difficult to answer and depends on many factors; just where the forces are applied on the body, how rapid their onset, what direction they are coming from, and the duration that they last [25].

A fundamental concept in biomechanics is that when a certain amount of energy is transferred that exceeds the ability of a human body to absorb it, an injury occurs. Similarly, when an ergonomics issue arises in a job place, it is general procedure to try to set a standard or guideline that restricts a certain job's demands or to clearly establish a threshold which not to go beyond. The incident at TMS is clearly cause for concern. We are used to seeing load and tolerance charts in the literature to describe thresholds, but before discussing the physiological factors of high G-acceleration a quick biography is needed to put a face on some of these thresholds. This history lesson lay in the Air Force Missile Development Center's pioneering post World War II biodynamics research led by Colonel John Stapp.

2.1 "The Fastest Man on Earth"

> *"...one factor is encouraging. There are only two models [male and female] of the human body currently available, with no immediate prospects of a new design; any finding in this research should provide permanent standards."*
>
> \- Col. Stapp, [23]

Such were Col. John Stapp's words when preparing to head up the AAF Aero Med Lab's research program investigating the effects of mechanical forces on living tissues, or more colloquially, the human body's ability to withstand G-forces. From 1946 through 1958, Colonel Stapp pioneered biodynamics investigations doing quantitative stress analysis of the human body to limits of voluntary tolerance of crash type impacts and deceleration [24].

Stapp's first project was analyzing plane crashes, or rather, why people were crashing in planes. Going into the project, the years prior and throughout the Second World War aircraft engineers and designers decided that humans could survive at a maximum of 18G [8]. Airplane cockpits then were all designed to withstand 18G impacts because if the person was already dead, why invest in stronger materials and structural support. Just how this figure was achieved, why, from whom, etc. immediately came into question by Stapp and his group who had been carefully reviewing vast amounts of accident reports that had started to reveal some contradictory evidence against this number. What they saw was that sometimes this G-tolerance number was too high and sometimes it was too low. In a series of well-documented accidents involving Navy pilots, the statistics and G-loads predicted that the pilots should have died from the G, however they lived through crashing into aircraft carriers and other aircraft at very high speeds. On the other end of the spectrum, there were many low magnitude and fatal crash landings that according to the numbers should have been survivable [26]. It became Stapp's theory that in many of these cases, the pilots probably survived the impact, however the seats, harnesses, and cockpits around them did not and were the real killers.

The group's ominous task was to determine human tolerance to deceleration and protection from crash forces. To do this, the team utilized a track mounted rocket-sled capable of accelerating 1,200 ft and then achieve various significant deceleration speeds via hydraulic brakes. The sled, named the "Gee Whiz" was constructed out of welded tubes and was capable of withstanding 100G of force with a stellar 50% safety factor [8] (see Fig. 2).

The test subject was supposed to be Oscar Eightball, a 185-pound test dummy (see Fig. 3). The Aero Med Lab had decided that all the tests would be run with dummies. Human runs were not even contemplated. It was thought

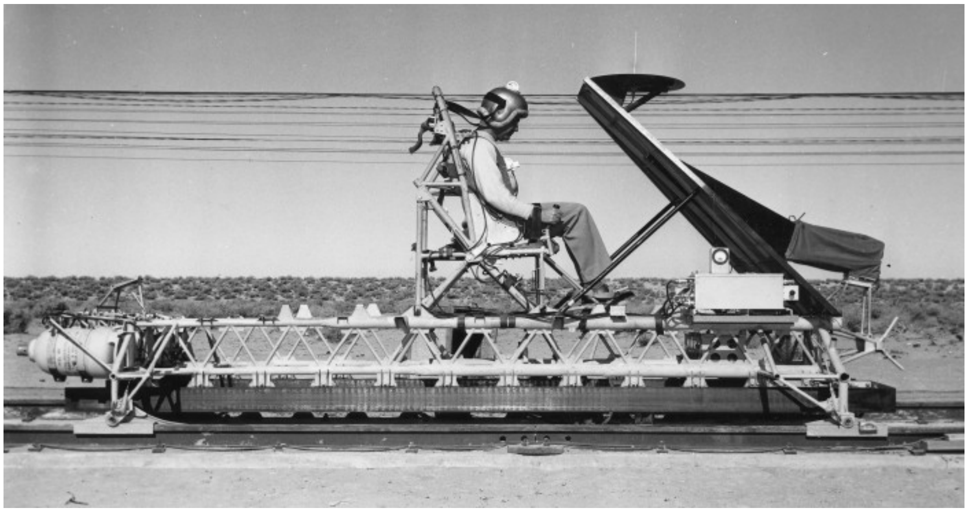

Figure 2: The 'Gee-whiz' rocket sled.

that dummies should be used because if humans die at 18G of force, then when using such high G with the rocket sled it certainly wasn't worth risking a human life. Colonel Stapp thoughtfully disagreed, he demanded that he would be the test subject.

The simplicity of his rationale was quite profound. A dummy could survive any oversight or engineering mistake, however it was that very risk of a person directly involved that should constantly be in mind when designing the equipment. The staff did not argue.

On the very first run Oscar accelerated along to 150 mph wearing only a safety belt. The brakes were hit, subjecting the dummy and sled to 30G, succinctly breaking the belt in half. Oscar's head stopped at the inch think windscreen but the rest of his body gracefully sailed right through the wooden windscreen and landed an impressive 710 ft away (right panel Fig. 3).

Methodically over the next eight months Oscar completed over 30 runs while the group worked out bugs and redesigned the equipment. Stapp felt they were ready for his first manned ride in December 1947. His first run hit 10G and afterward he commented that it was quite pleasant. The team began to vary the onset and duration of the G by manipulating the number of rockets on the sled and varying different braking setups. Sixteen runs were completely by August 1948, in which Stapp had been subjected to (and easily survived) not just the magic 18G, but a maximum of 35G. He felt he was still far from a threshold but these higher G did take their effect on the man.

The safety harness painfully dug into Stapp's shoulders at low magnitudes. As the G accelerations and rapid decelerations got larger, the harness cracked his ribs. Stapp suffered a number of concussions, lost dental fillings, broke his wrists a couple of times, and suffered a contusion to his collarbone. At accelerations greater than 18G, when facing backward, vision became blurry and eventually white as the blood in the eyes was forced into the back of his head. When facing forward he experienced "red outs", as blood was forced against his retinas breaking capillaries, hemorrhaging, and pulling his eyelids up [25]. Stapp was subjected to tortuous conditions, but more importantly, he survived. His team showed that humans could withstand forces in excess of 30G deceleration and just as importantly showed that seats, harnesses, and cockpits should be designed to withstand these forces as well. The 18G limit was refuted, and the Air Force listened.

Logically, Stapp's next project was to go faster. His next line of research focused on the fact that no pilot had been able to survive ejecting from a plane at supersonic speeds yet. It was unknown to researchers, and more importantly the pilots themselves, whether an individual could survive the ejection force, then the wind-blast, and finally the wind deceleration. Stapp had a new rocket sled built, this time using multiple stage rockets and much more powerful water brakes. On his final run, Stapp reached a peak velocity of 632 mph (20G) while being hit by two tons of wind pressure. He then hit two water brakes and came to a stop in 1.4 s experiencing a record setting 46.2G [25]. Stapp had suffered a complete red out and was just barely conscious. The jolt burst nearly every capillary in his eyeballs, he was blinded, but his retinas did not detach. He slowly regained his bearings and within a day his vision was back to normal.

Under his tenure, Stapp and his teams brought the importance of estab-

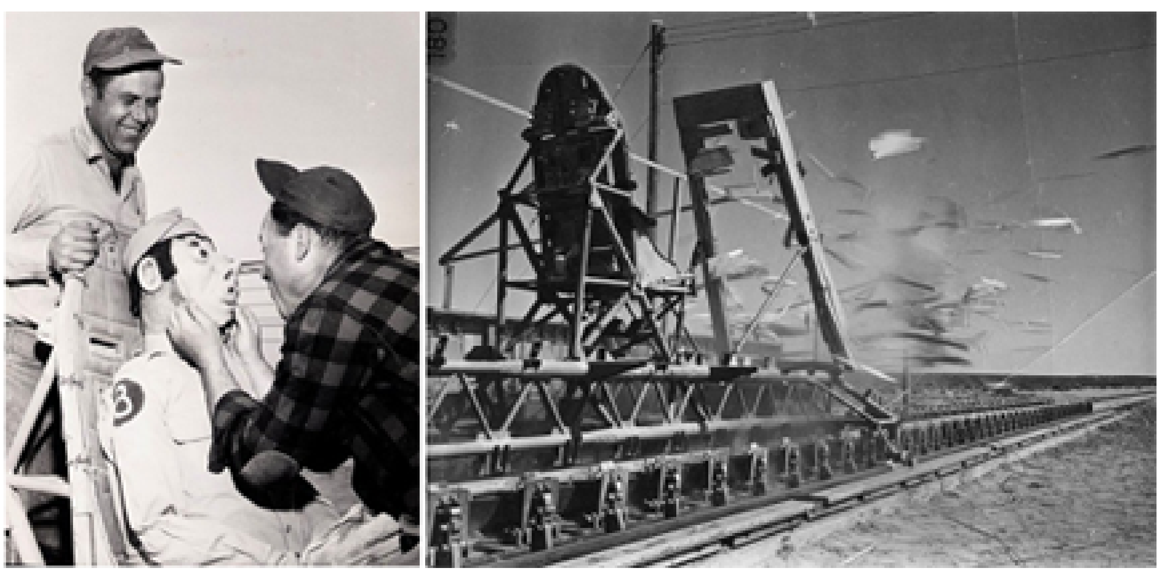

Figure 3: Hooray for physics! Oscar Eightball, before and 'in situ'

Figure 4: Col. Stapp Decelerating.

lishing human tolerance limits to impact forces to the forefront. Personally undertaking an incredible amount of hazard himself, Stapp's pursuits in quantitatively evaluating the relationship between the magnitude and rate of onset of these G-forces with their damaging and lethal effects on the human body had immediate as well as long lasting impact. Turning current engineering safety standards around, he showed that if appropriately positioned and secured, the human body could endure amazing amounts of crash forces. Stapp went on to champion his knowledge and research into the automotive domain bringing about many safety changes and establishing a conference that still bears his name today. John Stapp put a face on exploring this limit of human physiology and opened up a world of research in this branch of biodynamics.

2.2 Physiological Effects of High Acceleration

An article, published in 1919, by Dr. Head observed a phenomena of 'fainting in the air' in piloted aircraft ranging from the Sopwith Camel, Sopwith Triplane, and DeHaviland. Prior to 1920, experiments had shown that these blackouts "lasted about 20 seconds" and occurred when 4.5-4.6G were reached vertically [12]. What was being described became more commonly known as G-LOC, short for G-induced Loss Of Consciousness.

Stapp and his research team showed that the human body could tolerate a significant amount of force in short amounts of time such as in crash situations. The broader physiological implications of sustained and varied exposure to G-loads have many different and potentially dangerous effects. Rocket sleds aside, what is known about the effects of forces today comes mostly from human and animal studies in flight situations, centrifuges, swing, crash dummies, and computer simulations.

The physiological effects of G-loads vary with the magnitude of the acceleration, the duration, what axis of the body the G acts against (see fig. 4) and where on the body they are applied [24].

Such forces impact the body in different ways. A body can be impacted either positively or negatively in each directional axis. First, when a body is accelerated in the headward position, it is experiencing $+G_z$ or 'positive G'. Positive G_z pushes the body into the seat and in doing so drains the blood from the head toward the lower parts of the body. It becomes difficult to breathe as the ribs and the rest of the internal organs are pulled down which empties air from the lungs. Blood has to be forced harder to get to the the brain. This is quite a tiring ordeal. As seen with Stapp, the eyes being right below the brain are affected tremendously as well. The brain and eyes require O_2 and glucose to function properly, they both have a very small stored amount of glucose and almost no stored O_2 [28]. The bloodstream delivers a constant supply of both these nutrients which are essential for normal brain and eye function. Blood is constantly pumped to the head, against gravity, by the heart. This arrangement works well until the body is exposed to increased $+G_z$ which force the blood away from the head, no matter how hard the heart may work. The low arterial pressure in the eyes start having trouble keeping up around 2-3G [28]. The eyes first lose peripheral vision creating a tunnel vision effect and slowly cone vision will start to disappear until complete vision loss and blackout. The body is trying all it can to maintain cerebral blood pressure so individuals are usually still conscious. If duration of the G continues, unconsciousness follows shortly thereafter.

This phenomena is what Head reported on almost 100 years ago and is known as G-LOC (G-induced Loss Of Consciousness). As the G is reduced, consciousness is quickly regained resulting in a state of confusion. If the G-load is high and the onset is of short duration (such as greater than $+6G_z$ per second) G-tolerance is exceeded within a second or two. The individual will quickly pass from full capability to complete unconsciousness with no visual warning symptoms. These relationships are illustrated in Figure 6. The area

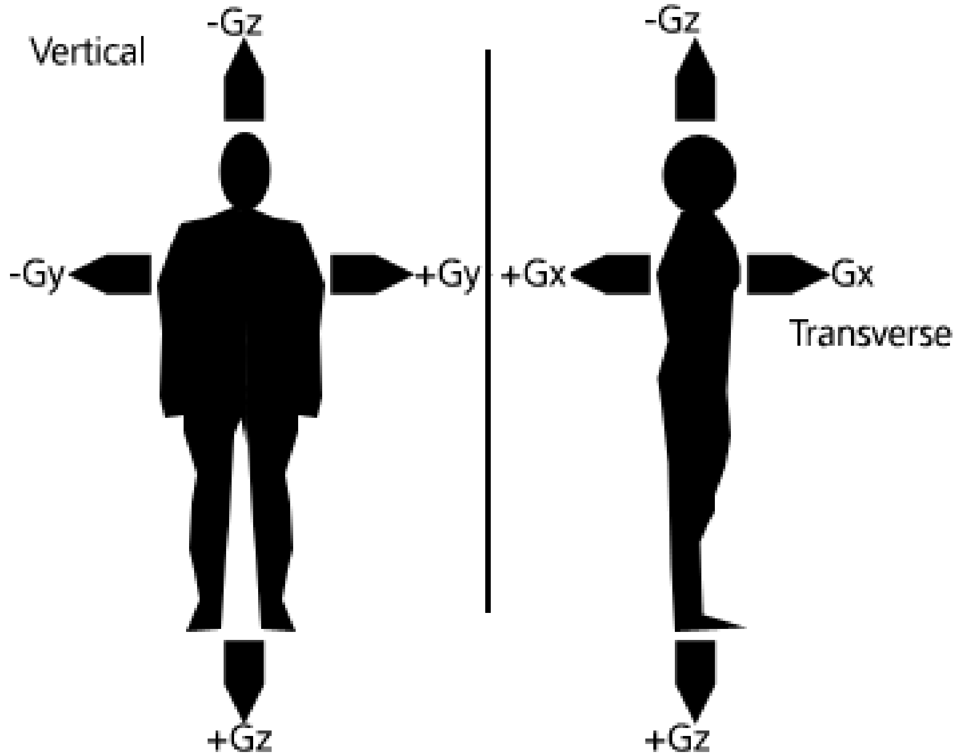

Figure 5: Directions of G-forces acting on the body.

above and to the right of higher curve is where the $+G_z$ and time results in unconsciousness (G-LOC) The grey area between these two curves is where visual disturbances without loss of consciousness occur. Below and to the left of the lower grey curve is the $+G_z$/Time zone where no visual symptoms or G-LOC occurs. The four lettered lines represent different rates of acceleration. Line C represents a gradual onset of $+G_z$ at a rate of 0.5G per second and shows that visual symptoms occur within 5 s and loss of consciousness about 1 s after that at $+4G_z$. Line D shows a slower $+G_z$ onset, visual symptoms occur after 16 s ($+4G_z$) and G-LOC will occur after 22 s when the acceleration will be at $+5G_z$. Rapid onset of sustained $+G_z$, as shown in line B will result in G-LOC quite rapidly after about 4 s with no visual warning symptoms. However, very rapid onset $+G_z$ that is not sustained at a high level, line A, may well result in no visual disturbances or G-LOC. This last feature is what kept many early pilots safe in Head's day, their early propeller-based planes limited their ability to maintain acceleration.

Conversely in a $-G_z$ condition, much like when standing on one's head, blood flow is forced away from the lower extremities and into the head. The body's built in defenses are not as refined as those for $+G_z$. With the increased upward pressure, the heart slows down. As Stapp experienced in his last ride, the first symptom of $-G_z$ is the visual "red-out" as blood is forced towards the head and into the retinal arteries. Rapidly changing from $+G_z$ to $-G_z$ (jolts) is equally disturbing and more akin to what terrestrial drivers would experience. Rapid jolts can lead to serious neck and spinal injuries. Constantly switching from $+G_z$ to $-G_z$ wreaks havoc on the circulatory system's ability to massively speed up and slow down trying to make up for these pressure gradients. The circulatory system's responses are not instantaneous and the individual can quickly lose consciousness in such a situation.

G-forces can occur in two other axes as well; transverse(G_x) and lateral (G_y). Transverse accelerations are directed across the body back to front and produce sensations of increased pressure on the part of the body that supports the weight. Transverse G (G_x) tolerances are much higher than in G_z conditions. With the onset of $+G_x$, significant magnitudes upward of $+20$ G_x can interfere with respiration and lung inflation movements. Similarly, $-G_x$ is not tolerated well at all, and also creates breathing difficulties [1]. Lateral G_y (pulling outward against the force of direction) is not a significant concern with problems in consciousness, however it does have a significant effect on the supporting muscles used such as the neck and head [19] [11].

The G_z conditions are the most important (and troublesome) to aviators, and towards the end of WW2 two predominant aids were utilized to deal with avoiding G-LOC; the G-suit and the anti-G straining maneuver [6] [9]. A G-suit is basically a set of balloons worn under the flight suit. As G-forces increase, a valve is activated and fills the balloons with air. The pressure then squeezes the legs and abdomen reducing the amount of blood that is forced away from the head into the legs. With a G-suit, accelerations of up to 8G can be tolerated for relatively long periods of time. There are also a number of anti-G Straining maneuvers which pilots are trained in. These involve specialized isometric muscle contractions and regulated breathing routines. There are multiple maneuvers to perform that all basically aim to teach pilots how to manually press with their lungs to squeeze the heart and force blood to the head. The general procedure is to flex the lower muscles and abdominals while taking a deep breath and holding it and then pull the G. Next, a strict breathing cycle of holding breath, inhaling exhaling, at different times occurs. The muscles have to be flexed throughout the whole maneuver. This is neither pleasant, easy, or natural and assumes one knows a priori or even when they will manually cause the G to be experienced.

There is a another bit of terrestrial programming that concerns the body when it is subjected to high G-forces; the human vestibular system and its integration with the human perceptual system. Not as much of a concern with pilots, but with terrestrial locomotion these effects are much more troublesome. Driving involves significant hand-arm-trunk systems as well as leg-trunk coordination. Limb muscles send positional information across proprioceptors that convey the locations of all the limbs to the brain and force sensors in the muscles called Golgi tendons tell the brain how hard the muscles are pulling. Together with the vestibular system the brain keeps track of the motion of the entire body [21].

All these actions are then (voluntarily and involuntarily) coordinated with the perceptual system to features of the environment. Vision provides a frame of reference that helps the muscles constantly adjust to maintain balance. As people move, visual stimulation in the form of optic flow and other environmental cues are highly integrated with the other parts of the vestibular system, one of the most prominent being located at the pressurized and fluid-filled inner ear. The structures in the inner ear constitute a kind of biological accelerometer responsible for maintaining body balance and equilibrium. The semicircular canals and vestibule structures inside sense movement (acceleration and deceleration) and static position. The three semicircular canals are perpendicular to each other, and each senses movement in each of the three spatial planes (XYZ). Different head positions produce different gravity effects on these hair cells. In turn, the hair cells for both position and movement create nerve impulses. These impulses travel over the vestibular nerve to synapses in the brain stem, cerebellum, and spinal cord. The nerve impulses then produce reflex actions to produce the corrective muscular responses. Changing direction rapidly, or accelerating rapidly both can confuse the system. A sudden loss of balance creates significant movement in the semicircular canals which in turn triggers leg or arm reflex movements to restore balance (a common occurrence in G-LOC is flailing and spastic movements) . Even more dramatic is when the information from the eyes is conflicting with information from the vestibular system the brain becomes confused [10]. Confusion, lack of balance, dizziness, and disorientation are all common side effects. Now introduce fluid imbalances from the increased accelerations, in conflict as well with perceptual cues, and there could be a bit of a problem.

Just how well an individual (pilot, driver, etc.) will be able to handle high G-accelerations comes down to just how aware they are of the issues in their domain. Familiarity with G conditions, types of exercise, and proper use of specialized equipment will decide just how well an individual can fare in these environments [9]. Before discussing the technology and aids that have been developed over the years to deal with these accelerations, and more specifically what is known and can be utilized in the context of driving, let's go back and try to review quantitatively and in depth just what forces the drivers at Texas Motor Speedway experienced.

3 A Funny Thing Happened on the Way to TMS

With a lack of published material yet to surface in the literature, in order to try to assess what happened at the Texas Motor Speedway that resulted in these accelerations and these symptoms, some quick basic physics lessons are needed (mostly for the benefit of the author). On the lowest level, there is a relationship between the force and the linear and angular displacement of the cars on the track. For a given measurable displacement, there is a measurable

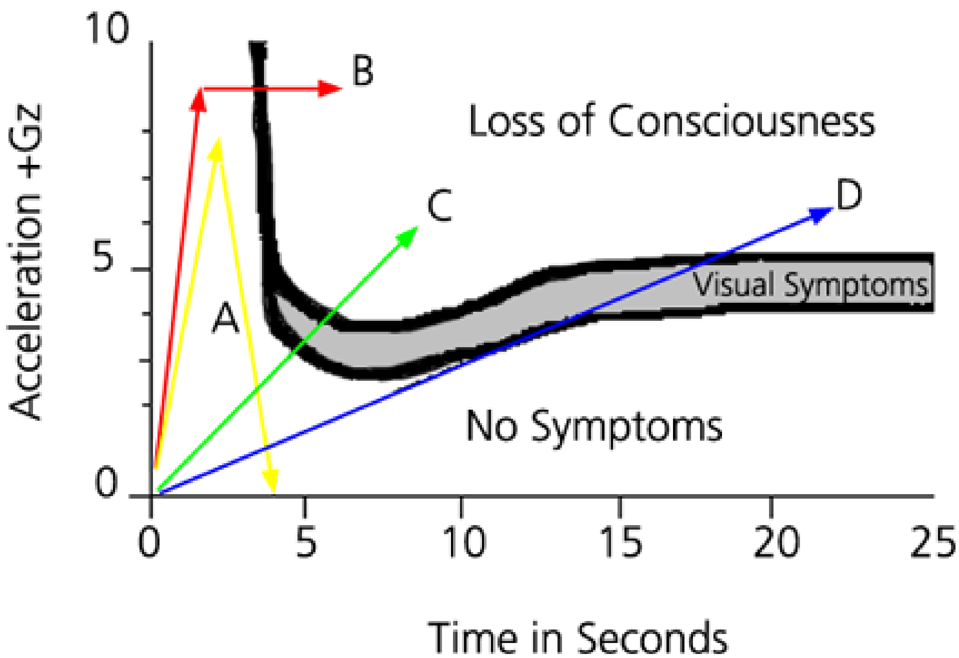

Figure 6: Tolerance to $+G_z$ Acceleration

force, and therefore a measurable acceleration; the G being the acceleration we are concerned with. The track designers are not stupid individuals and surely they must have calculated the accelerations required to make the turns at the speeds these cars can achieve. In order to calculate how high a turn should be banked they needed to calculate the amount of friction necessary to keep the cars on the track (or they just threw caution to the wind and banked the turns higher than everyone else, everything *is* bigger in Texas). The derivations for the formulas used can be found in the Appendix.

On an average oval track, drivers are constantly fighting inertia to keep their vehicles from careening wildly into the wall. The force that allows the turning comes from the friction between the tires and the road. By banking the curves a driver's sensation of being thrown sideways is reduced because the car is now sideways as well; angling the roadway inward causes the a car's weight to help pull it through the turn. The force of friction combined with the tilt make up the centripetal force. On an ideal banked curve, no outside forces are needed (i.e. requires no friction) to keep the car on the track.

When the coefficient of friction is zero (i.e., the road is very slippery), the maximum speed reduces to what is called the design speed (we will look at this again when discussing banked turns).

3.1 Feeling the G-forces

The banking doesn't really affect how we calculate the G-forces on the driver, but it is that angle which allows the cars to reach such high velocities. To calculate the G-loads felt by the driver, we need to calculate the normal force on the driver divided by the mass and then convert into multiples of G.

First, a quick review of what is known about the track itself so we can identify the pertinent variables and equations needed.

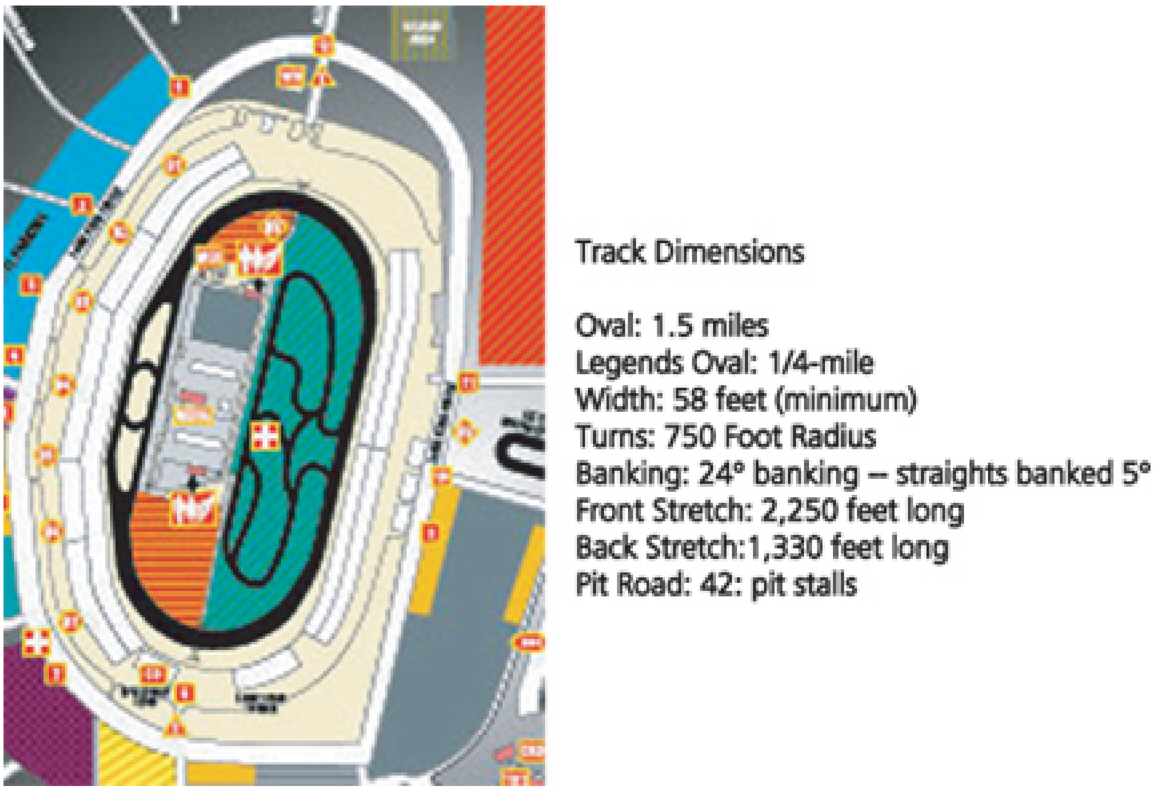

Figure 7: Texas Motor Speedway

Each banked turn has a radius of 750 ft (229 m). The track's corners are banked at an angle of 24°. The cars achieved velocities upwards of 236.9 mph (105 m/s). The coefficient of friction will depend on many factors, including the temperature of the rubber, the normal load on the tires, the rolling speed of the tires, the sliding speed of the rubber, and the composition of the rubber and of the contact surface. Even more significant, if the track was fresh, many small rocks were still sticking up which provides significantly more grip. For arguments sake, the CRC Handbook of Physical Quantities states that coefficients of static friction μ_s for rubber on various types of tarmac surfaces can range between 0.9

and 4 [15].

Now, we can attempt to verify those numbers.

$$105.893m/s = \frac{\sin[24] + \mu\cos[24]}{\cos[24] - \mu\sin[24]} * (9.8 * 229) = \mu \Rightarrow 2.42652 \quad (1)$$

The G felt is equal to the normal force divided by mass and then divided by G to convert to from $(m/s)^2$ to G.

$$F_c = F_{net,x} Acceleration = \frac{Velocity^2}{radius} \quad (2)$$

$$Acceleration = \frac{105.8943m/s^2}{229m} = \frac{49m/s^2}{9.8m/s^2} = 4.9967G \quad (3)$$

This is consistent with the numbers reported in the media. At ITS then, the corners were banked at 24° and let's again use our maximum G-value to calculate how much weight the horizontal G put on the tires.

$$horiz.G = \sin(24) * 4.9967 = 2.03G \quad (4)$$

Now, we also have to add the portion of earth's gravity also puts on the wheels while banked at 24°.

$$1G * \cos(24) = 0.9135G \quad (5)$$

The total G felt by the wheels = 2.03 + 0.9135 = 2.56G pushing down on the wheels (and the driver) through the turns. Missing from this figure is the major contribution of the car's aerodynamics which produces even more downforce. The wings on INDY cars are designed to produce a downward "lift" force which acts in addition to gravity such that the normal force is greater than the weight of the car when it is moving as well as increasing the force of static friction. On a road track setup, at 200 mph an INDY car can produce 4888 lb.'s of downforce, while on a short oval track such as ITS, one can produce almost 3000 lbs. These downforces could easily attribute for the reported G measured in the practice laps.

3.2 Discussion

When track designers and officials were surprised that the drivers were having trouble implies that even though the designers probably had a solid grasp on the physics involved in engineering the track, they maintained ignorance of the physiological effects of high G-acceleration on the drivers. The drivers showed symptoms that are well documented in other domains and literature concerning exposure to such forces.

Now compared to the durations and numbers seen in G-LOC there's some reason for concern; these are relatively low forces but they are being sustained for long periods of time. If we also look at the dynamics of the track and look at just how rapid the fluctuations from -G to +G are on it, the experience seems absolutely brutal.

Drivers were experiencing greater than 4G on an instantaneous basis and sustained in the area of 3 to 3.5G. Adding in the lateral G, which were 4.5G to 5G on top of that, it was well above the human tolerance level. The drivers were experiencing a combination of about 5G two-thirds of a lap. They were under these G-loads for about 18s a lap. They could tolerate it for short time, but once they got over 10-15 laps they started showing the symptoms.

The drivers take about 6.5 s to go down the front stretch, and then are almost immediately hit by close to 5G for the 6.5 s it takes to complete the turn. The back stretch takes another 4 s and they they are in another turn for 6.5 s of 5G again. The Texas Motor Speedway's track has longer turns with higher banks at each corner than most of the other tracks utilized. Taking into account the speed, position of the driver, radius, length, and banking angle of the turns of the speedway all in turn affect the driver. The driver's head position also plays a role in how they handle those turns. The higher banking of the turns confuses the relationship between their eyes, brain, and inner ear. The inner ear is telling the driver which way the G-forces are acting, however the force is not the typical down force of gravity, and the vestibular system is in conflict.

These higher bankings keep the G-forces more vertical (for the drivers), in fact significantly more vertical than other CART tracks (the Michigan speedway has turns at 18° and the Indianapolis Motor Speedway has turns at 9°), and they took their toll that day in April.

This is all quite alarming, but it is a relatively limited population that is affected. Before discussing solutions and alternatives to dealing with these forces, the question becomes should the average car driver have the same concern as fighter pilots pulling super maneuvers and race car drivers at poorly designed tracks?

4 Experimentation

In the spirit of participatory ergonomics, it would only be logical to get out into an INDY car and try to recreate these conditions and acquire some meaningful biomechanical data. Alas, due to powers beyond the author's control, the next best thing accomplishable was to find a reasonably fast car and put it onto a race track and take some basic accelerometer measurements to calculate different parameters and to assess risk in different driving conditions.

4.1 Apparatus

A GTECH Pro accelerometer was utilized to take inertial readings from a 3400 lb road car. Road and weather conditions did not allow track access, so a small closed lot was used.

4.2 Subjects

Two adult males with SCCA road course and race track experience drove the vehicle.

4.3 Procedure

On both oval and road courses, CART racers are subjected to extreme G-forces. We chose to gather information in three relatively simple situations; driving in a straight line and then rapidly decelerating, performing an emergency lane change maneuver from a constant velocity, and lastly accelerating in a small controlled circle. Unfortunately, we were unable to consistently attach the accelerometer to the driver's body and measure G-loads directly on the head, arms, legs, etc. so the space directly in front of the driver on the windscreen was used.

4.3.1 Linear Acceleration, Deceleration, and Lane Change

The accelerometer was attached to the car's windscreen and zero'd in each direction (XYZ) and set to record instantaneous data once a second. The driver accelerated from a stop to 80 mph and then performed a threshold braking procedure. This was performed three times while instantaneous and continuous G were logged and upon completion, the accelerometer reset. For the lane change trial, the car achieved a balanced load at a maintained 70 mph. At a set point, a quick and accurate avoidance maneuver was performed and then the car was corrected and recovered onto its original course heading. Instantaneous and continuous G were again logged on each run and the accelerometer reset.

4.3.2 Centripetal Acceleration in Small Radius Circle

The accelerometer was again attached to the car's windscreen and zero'd in each direction (XYZ). Transverse and vertical G did not fluctuate rapidly after two pilot runs, so for the actual trial only lateral acceleration was recorded at a 1s delta. The driver navigated a small 30' radius circle maintaining as much speed without losing traction. Instantaneous and continuous G were logged and the accelerometer reset upon completion.

4.4 Results and Discussion

Going into the study, it was felt that results might not be substantial, especially considering the lack of high banked turns as well as the minimal amount of downforce a streetcar produces. Furthermore not being able to use a track combined with the weather also severely impacted the magnitude of the recorded data.

The maximum and minimum G values recorded can be seen in Figure 8. Most of these are instantaneous values and could not be maintained for over 2 s. The largest G felt was on the transverse axis and in the linear acceleration and deceleration trials. Braking caused an instantaneous peak of -3G, and in

	Direction and Accel. in G					
Trial	x_{hi}	x_{lo}	y_{hi}	y_{lo}	z_{hi}	z_{lo}
Linear Path	0.78	-3.0	0.04	0.0	1.5	1.0
Rapid Lane Change	0.40	0.0	0.51	0.28	1.09	0.94
Centripetal Path	0.28	---	0.84	0.11	1.0	---

Figure 8: Accelerometer Data Collection

one run maintained -2G for just under 2 s. The power of the braking was also reflected in the vertical axis pushing down 1.5G briefly before returning to normal earth gravity at 1.0G. In the rapid lane change maneuver the initial jolt in the lateral Y direction peaked at 0.51G, and vertical just peaked over gravity at 1.09G as the car's load changed. Lastly, in the circular trial, the lateral high of 0.84G was also continuous.

From a qualitative standpoint, the drivers asserted that the G-loads that they could feel the most were the vertical and transverse when initially accelerating and rapidly decelerating. Similarly, the transverse G-loads were felt the most in the lane change and the centripetal trial. The only condition drivers complained about was the small circle in the centripetal condition; it was slightly dizzying in spite of any significant banking or high speed.

The conditions tested are not the most ecologically valid compared to common everyday driving, let alone compared to a CART road or oval course. However, it does show that with a normal car in small isolated situations it takes a lot of effort to achieve significant G-forces and takes even more difficulty to maintain continuous G of this magnitude. It seems that G-forces in street carr can continue to be the concern for only crash engineers for the time being. The cockpit of the vehicle was well designed from a reach and feel perspective and easily afforded rapid and precise wheel movement, gear shift, and pedal manipulation. The seats provided comfortable shoulder, lumbar and back, and neck support for the driver. The long term effects (like a 250 lap CART race or a long road journey) between such G-loads and this cockpit design could not be evaluated but as an initial investigation, this experiment did show small ranges of forces that the body experiences in certain ergonomic situations that could be taken into account in lieu of potential cumulative trauma disorders when designing and evaluating future cockpits.

5 General Discussion and Proposed Solutions

The first and most obvious solution to the problem at TMS is quite simple, remove the problem altogether and lower the banking angle on the turns. A nice solution but the envelope is being pushed in racing as to just how much the human inside(s) can take. Anyone that is subjected to such G-forces could suffer from these symptoms or worse. If these symptoms pop up in a car and exacerbate, the car can crash. Crashing a car over 200 mph into a solid wall or 20 other cars, can be a health hazard in a race.

What became obvious at TMS is that the human threshold can be reached with certain speeds on certain tracks. Either tracks need to be designed with these limits in mind, or the designers need to cater to the driver-specific issues. The aviation knowledge base has shown that to increase tolerance to G-loads, pilots must practice regularly, make strenuous physical effort, and at times employ mechanical aids [2]. Components of each of these could greatly alleviate high G symptoms if the race governing bodies, engineers, and vehicle manufacturers want to continue to push the envelope of speed.

Ergonomics has traditionally come second to safety in modern INDY cars. Recently, published research looking at physiological data and musculoskeletal disorders in race car drivers has really started to take off. Normally, one can look at the ergonomics data and then establish guidelines and thresholds. In this situation things are slightly more difficult; the human thresholds are readily known, but there is relatively little field data so to speak. The goal in proposing these solutions then is to see just where MSD problems areas are popping up in drivers and attempt to address those along with the mechanical solutions suggested to augment high G-tolerances.

5.1 Potential MSD's in the Open Cockpit

High performance driving requires a great amount of physiological exertion on similar levels to elite athletes [14]. At peak driving speeds, heart rate and O_2 uptake levels are high and so are lateral and vertical G-forces (averaging about 4 to 4.5G). In such a work environment drivers are susceptible to a high magnitude of vibration, shock, and increased muscle use throughout their bodies [16] .

In the small open-wheeled open cockpits, safety is everything, however, the cockpit is also very cramped especially with regard to leg room. There has been an increased amount of research recently into the ergonomics and biomechanics involved in race cars specifically, and its becoming evident that it is very difficult to effectively balance safety and comfort. INDY cars are safe, very safe. A chassis must be aerodynamic and allow for numerous weight distribution, suspension, wheel loading and wing adjustments. Above all else, these cars must protect the driver. Carbon-fiber and aluminum composites form the structural tub that makes up the cockpit. When a car crashes, it disintegrates. The cars are designed to tear apart slowly and distribute the force of the crash and decelerate the G-forces [4]. The strongest parts of the chassis absorb the crash forces with ease. Crashes in excess of 100G are not uncommon, and drivers easily walk away from them without a scratch.

In these tiny confined cockpits, a lot is done well biomechanically speaking. The driver is never really fully extended, the neck, arms, shoulders, and legs are all in relatively natural positions, back posture is individually designed for, arm muscles are supported, and moments tend to be small. According to Porter and Gyi, the least amount of lower back related musculoskeletal disorders correlated with the amount of adjustability inside the car cockpit and the presence/absence of power steering [20]. In an INDY cockpit, the car is built around each specific driver and many of these MSD factors are minimized. One glaring issue however, is the temporal nature of the situation; there is no rest, and when there are short breaks, the drivers cannot move. All bets are off however during crashes and adverse conditions where trauma can be a much larger issue to tackle, so we shall concentrate briefly on two specific areas of physiological interest from a cumulative trauma perspective.

5.1.1 The Neck

Seats are molded out of similar aluminum/carbon fiber composites with integrated headrests in a semi-supine form and angled backwards at 45°. The headrest area protects the sides and back of the head and attempts to minimize tension-extension and lateral bending loading. The harness belts are integrated into the seat and provide decelerative forces over a large area of the body while keeping it in an ideal impact position. With all of this however, the loads and torques felt by the neck are still very high. Recently F1 and CART have both mandated the HANS device (head and neck support). HANS restricts head movement via tethers attached to the drivers helmet. By restraining the head to move with the torso, head weight and forces on the neck are dramatically reduced. There is concern that if implemented improperly the device could cause an even more abrupt deceleration in a crash, but the real issue is the vibration and G-loading that it is experiencing. The combined weight of the head and helmet are both pulling at the neck. The neck is essentially a wide open target for MSDs here and even more troubling is just how difficult an area it to stabilize without having significant adverse effects on safety and comfort. HANS-like devices are continuing to develop and be tested, and could potentially assist this problem area.

5.1.2 Arms and Shoulders

Motions in the cockpit involve a lot of rapid pushing and pulling and incredible amounts of arm and shoulder strength. The seat that the driver sits in is custom molded to his body, and the position is more like lying on his/her back in a semi-supine position rather than sitting in a traditional car. The cockpits are pretty well arranged for the arms and shoulders from a biomechanical standpoint. The shoulders are slightly pinched forward, elbows are positioned at the waist with the arms bent slightly upwards resulting in the wheel just above chest level. The shoulders are abducted roughly 30° and are in a good position to provide maximum strength and endurance. The wheel is relatively close in front of the body and slightly elevated providing an effective moment for the arms and decent length-strength relationship. Elbow support is provided from the sides of the tub.

Drivers stretch their arms forward to manipulate the steering wheel, gear lever, and wheel buttons, and, during a long race this can be exhausting. There is an incredible amount of tension in the upper limbs during a three hour race with no rest, and this fatigue takes its toll. The driver has to maintain periods of persistent high grip forces, but these are varied often with gear shifts and pit stops. The elbows and forearms are supported and the wrists are in a relative neutral position with slight flexion when using the wheel. Tension and prolonged grip aside, the driver's gloved hands can experience a great deal of vibration as well. It should not come as a surprise then upper limb injuries are becoming common with race drivers including forearm compartment syndrome, wrist pain, de Quervains disease (tenosynovitis of the thumb), and palm abrasions [18] [17]. Materials and controls change often in these situations, so causality is difficult to assess. In FORMULA 1 Masmejean et al found that before switching to wheel mounted semi-automatic gear change, many drivers suffered from microtrauma and repeated palm abrasion [17]. However, drivers who had started after the gear-change moved, had no complaints. Steering wheel material has become a lot smoother and compressible recently and more and more buttons have been integrated into the wheel itself. This can go a long way in alleviating current and preventing future problems. In addition, efforts can be made to better fit the steering wheel diameter to fit each driver's hands as well as improving the wheel material itself to maximize grip strength per driver. To address the hand-arm vibration, wrist pads could be used if they do not impede motion [17] and switching to more vibration reducing engineering materials could further help.

5.2 Physical Conditioning

Drivers need to keep the blood up in their heads. G-suits can help for the lower extremities but the Air Force has lately been discovering the merits of mixed anaerobic and aerobic training and the importance of upper body muscles for sustained flying [13]. Even more so, in combination with the MSD's that are starting to show up, strength training could be used to better isolate certain areas so they are not as susceptible to break down. To increase G-tolerances there needs to be increased blood pressure and heart rate; isolating the upper body is important for this. The Air Force has recently been pushing resistance and strength training, which builds mass and strength in skeletal muscle groups. I telephoned a close friend, a recently retired Air Force colonel in charge of recruitment, about the details of training for such flight activity.

High-intensity strength training increases the body's ability to withstand high G-forces for longer periods of time and moderate aerobic training decreases the recovery time needed between G exposures.

During aerobic training, the cellular processes that convert O_2 and glucose into energy can supply all of the energy needed for the work being done. Aerobic exercise basically trains the heart. It improves the heart's pumping ability and overall cardiac output. Aerobic training has little effect on the muscles, for that, anaerobic training is required. Different metabolic processes are used and the workouts are based on strength exercises that put certain muscles against a resistance, such as in weight training. Internally, muscle fibers are damaged, repaired, and then enlarge in size and their ability to do work is heightened.

An average Air Force workout specifies key areas to train, which translate well to an automotive environment. First, chest muscles form the foundation of upper-body strength. Arms and shoulders are essential in both airplane and race car cockpits. An inability to raise the arms has been documented in some post race situations on tracks [18]. This is suggestive of deltoid muscle exhaustion. Strong stomach muscles help to prevent back injuries as well as provide better breathing capability in stressful situations. The legs are another key area in both plane and driving situations. In regard to manually regulating blood pressure, aircraft pilots have been known to strain their calf muscles to control the flow of blood to the leg. INDY drivers are not as fortunate such that they are using their legs constantly navigating between the three pedals. Rapid and precise movements are essential here. The neck and spine are severely stressed by the horizontal and lateral high G-loads experienced. The additional helmet weight and flying/driving equipment put quite high loads on it. Strong neck muscles are critical [22]! A strong neck, which can be targeted with isometric exercises, makes head movement easier under high G-loads and can help prevent injury from the periods of jolts experienced.

These race car drivers are generally a very fit population. They are exerting themselves at similar levels of elite athletes, but just how much training they undergo, and more specifically whether it is targeting such systems that should be concerned with G-tolerance is a good question and needs to be addressed. Awareness is the key. Just like in the workplace, physical conditioning can be difficult to mandate and monitor, and it does vary from person to person. The Air Force recommends such conditioning but its original answer to high-G lies in mechanical solutions.

5.3 Mechanical Aids and Combined Solutions

Under excessive G-loading, two affected areas are of concern; sudden shifting of the body's position upsets the fluid in the inner ear causing the lightheadedness and dizziness, and the amount of blood going to the brain is decreased. The goal is to reduce the forces acting on certain areas of the body as well as to assist and act upon what is going on inside the body.

Let's start back up at the head. Helmets, unlike in NASCAR are required in INDY. Not only do they have to be aerodynamic and stable while caught in 230+ mph slipstreams, but they have to be safe as well. From a functional stand-point helmets are designed to distribute the forces the driver experiences (in both driving and crash situations) over a wide surface area to protect the brain. Emerging evidence has claimed that breathing 100% O_2 can slightly increase G-tolerances [7]. By increasing O_2 stores in the body in this manner, the O_2 and nutrient rich steady supply of blood that's desperately needed could influence pressure as well as delaying the production of lactic acid (tense muscles won't cut off their own supply so quick). This could buy some of the precious time before the heart catches up and regulates again as well as potentially guard against cumulative trauma disorders in the repeatedly tensed muscles. Next, some sort of neck support could be integrated with the helmet device as well. Combining tethers with shock absorption from the shoulders up could greatly minimize the vibration and jolts experienced by the neck.

Now, the next goal is to keep blood up there in the head and taking some of that excess work away from the heart so that it can continue to deal with the existing physiological stress. Moving underneath the head, the goal is to combat all the blood being displaced and try to assist the body in maintaining proper blood pressure. The aviation answer 50 years ago was the G-suit. With a G-suit in aircraft, accelerations of up to 9G can be tolerated for relatively long periods [5]. The traditional G-suit has bladders that fill with air to prevent blood from leaving the head, mostly adding pressure to the abdomen and lower limbs [2]. G-suits are uncomfortable and hot, but a necessity for a fighter pilot. Equally bulky are the many layers of flame retardant clothing racers have to wear. Combining more recent G-suit technology such as the Libelle G-Multiplus flight suit, which utilizes four columns of liquid [5] and offers significant protection (up to 6G) and is considerably less bulky than traditional compressed gas based suits. Lessons learned in aviation from the G-suit could be integrated into the harness system in the cars as well. Integrating another belt either as part of the restraint system or as a separate strap could be utilized to to provide additional abdominal compression that is useful in keeping blood from pooling in the lower extremities. This could all be slightly risky however, messing around with blood flow and changing pressure location might not be a wonderful idea especially with the MSD and CTD data emerging. With the extreme loads the neck is taking, those muscles need a steady supply of blood as do the leg and arm muscles to carry out their work. These G-suits need to be precisely 'tuned' to inflate and deflate to the specific body areas instantly, and just as importantly, the MSD and CTD risk factors need to be minimized.

5.4 Conclusion

Texas was a wake-up call to many involved in racing. Amongst a slew of accidents in other leagues, safety concerns have come to the center stage. At TMS a problem reared its head that nobody had ever thought would happen. This problem was very well documented in another domain, and in two fields where there has historically been a significant amount of overlap, aviation and automotive, and it is outright surprising no one saw a potential for concern. Luckily in this case, resolute action and safety consciousness prevented this race from occurring and thus brought the issue into the light of day.

Much like the track conditions that led to the canceling of the race, the solutions I proposed may or may not solve the problems at hand and could very well create new problems, but without testing and research we will never know until they are contemplated. The new push in safety culture in motorsport that has emerged from the prominent crashes in the US recently has opened up research that has traditionally been behind closed doors. From a personal standpoint, the last time I wrote about racing safety it was notably more difficult finding specs, figures, and documented cases in any literature, let alone published journals. Now the CART Director of Medical Affairs is even publishing. Research in the domain has typically been of the "if it gives any sort of advantage, we're holding on to it and keeping quiet." From analyzing threshold levels to gathering physiological data and diagnosing musculoskeletal disorders, it is promising to see the concern for many different types of safety opening up.

Since man started locomoting faster and faster in the automobile, significant effort has been put into keeping safe inside. It is now thought that a valuable part of keeping safe must include fitting that vehicle to the driver as well. It is only through rigorous study in many different fields, quantitative investigation and analysis, and open communication of research that better safety practices can emerge.

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APPENDIX

A Acceleration, Centripetal Force, and Friction

The name of the game here is circular motion, and we have to look at how friction and centripetal force play in these situations. As was discussed earlier, a G is merely an acceleration. We can simply take various accelerations and convert them into a G-force by comparing it to the acceleration produced by gravity. For now, we are not as concerned with the linear acceleration in the straightaway, but more so the centripetal acceleration in the corners. For conventions sake I am going to describe vertical loads in terms of Y and horizontal in terms of X in two dimensions which correspond to a Z up axis real world.

The net force on a car traveling around a curve is the centripetal force, directed toward the center of the curve.

$$F_c = M\frac{v^2}{r} \tag{6}$$

For a level curve, the centripetal force will be supplied by the friction force between the tires and roadway. If there was no friction the car would slide towards the outside of the curve, so the friction opposes this tendency and points down the slope.

$$F_N = Mg = (M)(9.8(m/s)^2 \tag{7}$$

On a flat curve, the centripetal force is supplied for by the force of friction F_f

$$F_f = \mu FN \tag{8}$$

$$F_f = \mu M 9.8(m/s)^2 \tag{9}$$

$$F_f = F_N = F_c \tag{10}$$

This lets us solve for μ such that any coefficient of friction greater than μ will keep the car from slipping.

B Banked Turns

Things are slightly different in a banked turn. A banked turn can supply the centripetal force by the normal force and the weight without relying on friction. Banked turns are designed for a specific speed. With no friction, a car can travel in a radius at a constant speed. Without friction, the roadway still exerts a normal force N perpendicular to its surface.

The downward force of the weight w is present. Those two forces add as vectors to provide a resultant or net force F_net which points toward the center

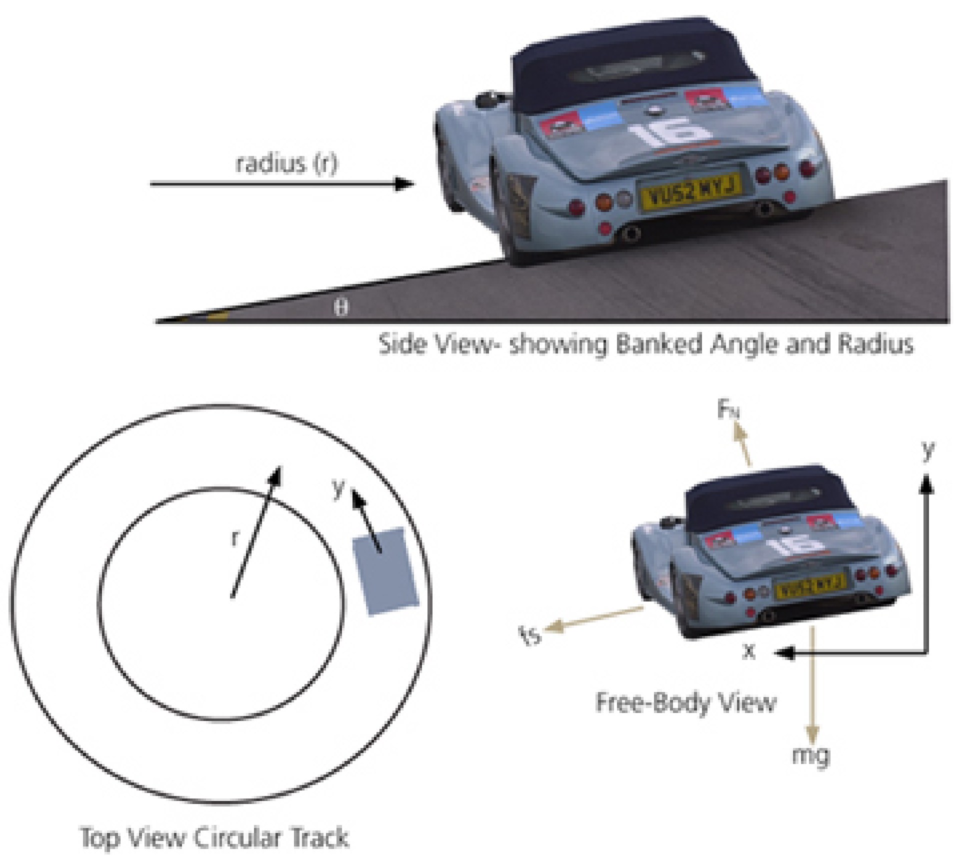

Figure 9: Circular Motion Illustrated

of the circle; this is the centripetal force. Since we are interested in the force that points toward the center of the circle, we choose a coordinate axis that lies along that direction. There is no acceleration in the y-direction so the normal force counters the weight of the vehicle, which makes the net force the only unbalanced force, which is the centripetal force, and now the sum of the forces in the y-direction is zero.

Banked curves are designed for a specific speed, and this is known as the design speed. With no friction, a car can travel in a radius at a constant speed at a certain angle.

$$\tan(\theta) = \frac{v^2}{rg} \tag{11}$$

To see how the design speed is derived:

$$F_{net,y} = n\cos\theta - w = 0 \tag{12}$$

$$n\cos\theta = w \tag{13}$$

$$n = w/\cos\theta \tag{14}$$

$$F_{net,x} = n\sin\theta \tag{15}$$

$$F_c = \frac{mv^2}{r} \tag{16}$$

$$F_c = f_{net,x} \tag{17}$$

Substituting that in then gets us:

$$F_c = \frac{mv^2}{r} = n\sin\theta = [w\cos\theta]\sin\theta \tag{18}$$

$$F_c = \frac{mv^2}{r} = w\frac{\sin\theta}{\cos\theta} \tag{19}$$

$$F_c = \frac{mv^2}{r} = mg\tan\theta \tag{20}$$

$$\tan\theta = \frac{v^2}{gr} \tag{21}$$

C Max Speed on a Banked Turn with Friction

In a banked turn while accounting for friction there is a range of speeds at which the driver can negotiate a curve of given angles. In most cases the coefficient of friction is sufficiently high, and the angle of the curve sufficiently small such that traveling too slowly around the curve is not an issue. On the other, traveling too at too high a velocity is an issue. We can solve for this maximum velocity around a turn.

$$V_{max}^2 = \frac{(\sin\theta + \mu_s\cos\theta)}{(cos\theta - \mu_s sin\theta)}\ gr \tag{22}$$

The derivation achieved is similar to that from Equation 6.

$$F_{net,y} = F_n\cos\theta - mg - f_s\sin\theta = ma_y = 0 \tag{23}$$

We can then substitute and solve for the normal force.

$$F_N = \cos\theta - \mu_s F_N\sin\theta = mg \tag{24}$$

$$F_N = \frac{mg}{\cos\theta - \mu_s F_N \sin\theta} \tag{25}$$

We're solving for the maximum speed at which the car can go around the curve. This will correspond to the static force of friction being a maximum, which is why it's valid to say that $f_s = \mu_s F_N$

In the x-direction, to calculate force

$$F_x = F_N \sin\theta + f_s \cos\theta = ma_x = m\frac{(V_{max}^2)}{r} \tag{26}$$

We then put in the friction variable and the equation for normal force:

$$\frac{mg\sin\theta}{(\cos\theta - \mu_s \sin\theta)} + \frac{\mu_s mg\cos\theta}{(\cos\theta - \mu_s \sin\theta)} = m\frac{(V_{max}^2)}{r} \tag{27}$$

The mass terms cancel out and we can solve for maximum speed:

$$V_{max}^2 = \frac{(\sin\theta + \mu_s \cos\theta)}{(\cos\theta - \mu_s \sin\theta)}\ gr \tag{28}$$

As can be seen, as the coefficient of friction approaches 0 (no traction = slippery) the maximum speed approaches the design speed (Equation 6).

Banking a turn allows some of the G forces created in the turn to increase the weight on the tires which also increases their traction. We can then figure out what portion of the horizontal G adds weight to the tires.

$$\text{from } \Sigma F_y \Rightarrow \frac{mg}{\sin\theta} = A\ Sin\ \theta \tag{29}$$

In addition, a portion of the 1 G from Earth's gravity puts more weight on the tires. The G forces due to gravity can be calculated by:

$$A = 1g\ cos\theta \tag{30}$$

It is then a summation of these G forces and the downforces that the aerodynamics of the car produce that keep that car stuck on the ground and more importantly, these same horizontal and vertical forces are acting upon the driver in the center of it all.