DRIVING SIMULATION

A Kriss Motors DIY Brief

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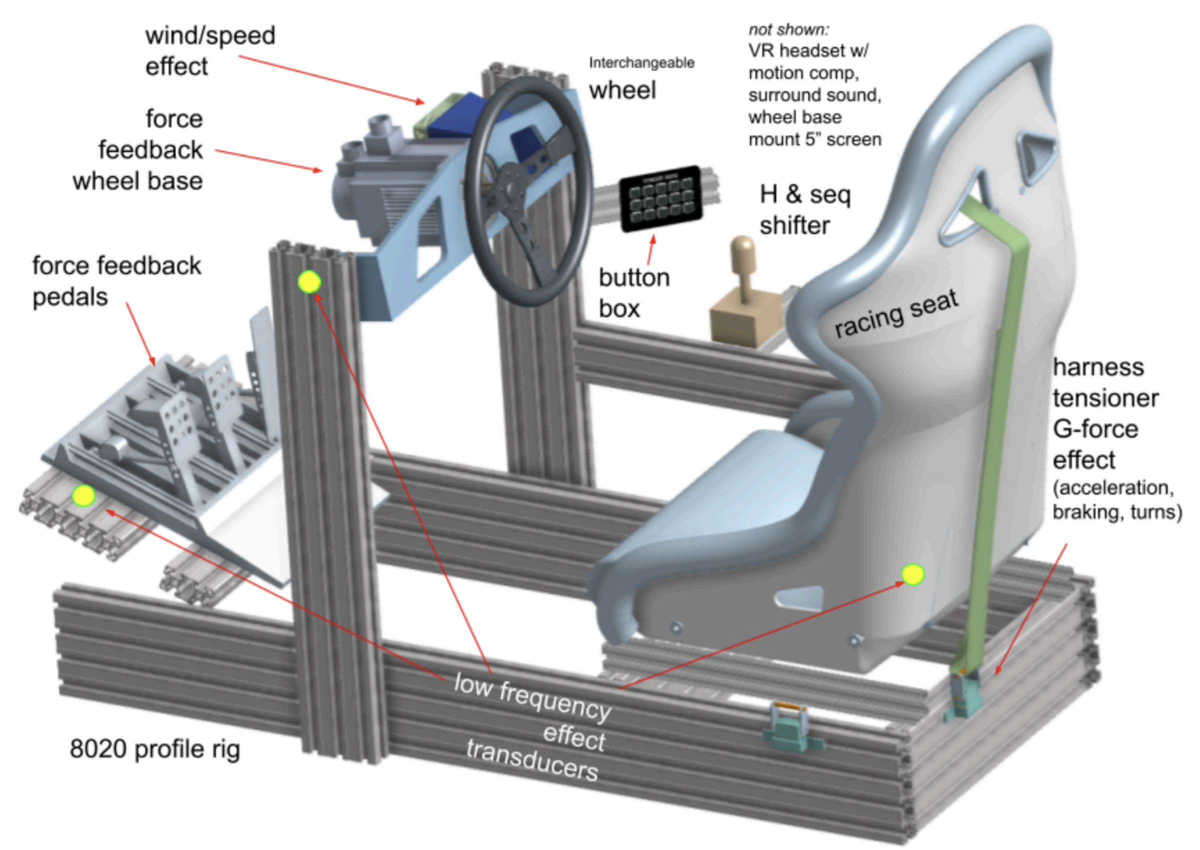
Introduction

As technological evolution continues to explode along an exponential trajectory, the boundary between real and computer-induced perception becomes increasingly blurred. Determining just how far this boundary can be penetrated to induce a state of total immersion — referred to as *virtual reality* — is the subject of much experimentation.

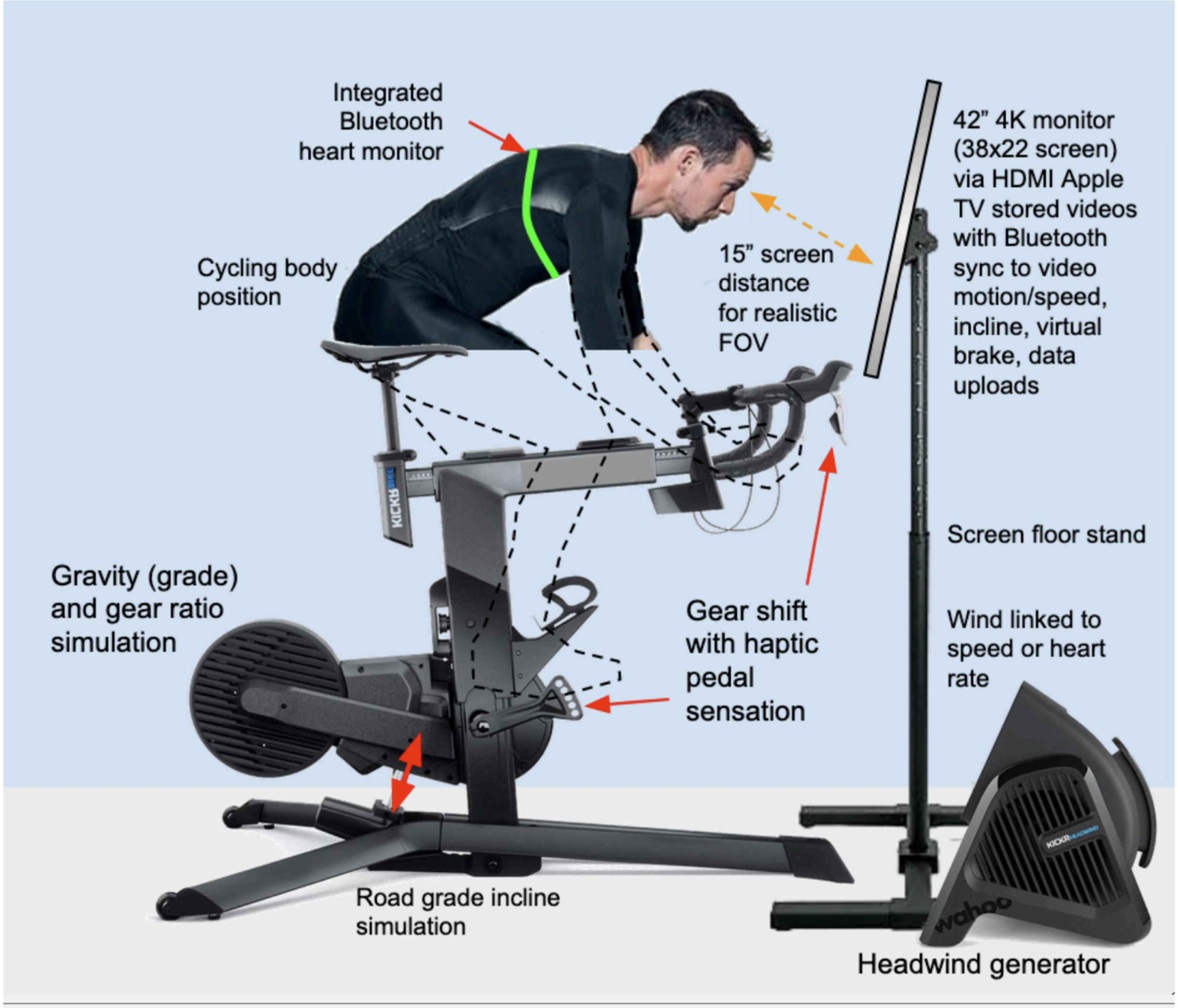
More specifically, can a simulated environment suspend disbelief to such an extent that the driver thinks his automotive experience — or a cyclist his riding experience — is actually real in terms of visual, auditory, and haptic perceptions?



Will a contraption like this create a total immersion simulated driving experience?

The key technical advance underscoring our confidence that this objective can be achieved today within the bounds of a DIY budget is the maturing development of virtual reality (VR) headsets. Introduced in the 1990s, early versions failed commercially due to severe limitations on functionality and visual acuity.

The first product to overcome these early obstacles was the *Oculus Rift* with its beta version in 2013 and initial commercial release in 2016. Significant progress since then promises to deliver visual simulation at a level that hopefully "bypasses" the real/artificial mental barrier by 2027.



Can a setup like this create a total immersion simulated cycling experience?

Fortunately, driving or cycling motion simulation is somewhat easier to address than some other VR domains like outdoor exploration, group interactions, or fantasy adventures. Why?

- a seated driver/cyclist limits both the physical space and body movements that must be monitored and incorporated in software models; in fact, the seat as well as a belt restraining system (or cyclist pedal clips) can provide excellent haptic simulation if they are identical to actual racing gear
- visual cues like road surfaces, cockpit instruments, and passing scenes, can be replicated with sufficient detail to insure immersion

- the acoustic environment is well documented — mostly road and engine noise — and reproduces well with consumer-level equipment
- driving/cycling is a solo activity in terms of human interaction; other vehicles on the road “interact” only within the realm of physics, not emotional complexity
- communication — when it exists at all — is straightforward and extremely rule-based (like racing starts and finishes)
- everyone knows what driving or cycling feels like; if the simulation matches the brain’s real-world memory then total immersion may emerge as a result

Apart from VR headset-related challenges, the most difficult aspect of motion simulation involves how we feel gravitational forces during acceleration, braking, and turning as well as our perception of steady speed (where there are no G-forces) and haptic triggers like the difference between smooth asphalt versus a gravel road. Force feedback effects become necessary to mirror real-world steering wheels, gear shifters, and pedals in addition to the importance of the tactile 3D feel of these controls on our hands and feet.

Since two-thirds of brain activity involves visual perception, we start this journey with an examination of human sight.

Sight

Curved tri-monitor setup

For driving simulation, the alternative to VR headsets for visual input are curved computer monitors, typically three linked together in a semicircle, positioned as close to the simulator seat’s field of view as practical given space and equipment constraints.

Given the constraints of a rig, screens are usually placed many feet away, and thus the largest possible screen size is desirable.

However, 2D screens cannot ever match the 3D depth realism of binocular VR no matter how many pixels are deployed.

Over the next few years as VR comfort issues are addressed, headsets will likely replace monitors (except for setup, tuning, and similar tasks where a keyboard and mouse provide the best interface).

Since 2018, at least eighteen different VR headsets have been introduced to the consumer market. Headsets designed for military, industrial, medical, and other specialized fields will be excluded from this analysis as well as those with a MSRP over $2000. In addition, only headsets powered by Microsoft Windows operating systems and without battery packs (that is, an external power connection is required) make our list. VRCompare maintains an excellent summary of all VR headsets.

For cycling, VR headsets are much less practical since the head is typically pitched forward and down, making them less comfortable to wear for extended periods. The alternative is to place a flat screen extremely close in — about 15″ — to replicate a comfortable field of view.

Visual realism

VR promises nearly perfect visual realism due to three factors that cannot be replicated by any display monitor:

1. Depth perception: three dimensional representation due to binocular vision (stereopsis)
2. World coherency: entire environment shifts with head/eye motion
3. Speed perception: peripheral field of view not distorted

Accurate depth perception is absolutely critical for simulation realism, especially when negotiating a curve or avoiding obstacles. Display resolution alone will never achieve the sensation of space achieved by stereopsis.

Unless the entire 360-degree environment is linked to the visual system, the degree of immersion will have limits. While the space around a display screen fades from conscious awareness, the fact that the floor, walls or ceiling doesn't move with projected images always reinforces the fact that the experience isn't "real".

We experience steady speed (no G-force cues) largely through our peripheral vision.

The quality of peripheral inputs matters. To be realistic, the peripheral field of view must maintain the expected geometric relationship to the center primary vision field (only 5% of what we see), and this is essentially impossible with 2D displays even with the latest curved form factors. The pixel distance from the eye's front focus must appear equal to the side distance, something only achievable with VR technology. If the field of view is limited, as is the case currently with many VR headsets, speed appears lower than it actually is. This is clearly an issue that VR technology must address.

In fact, given that speed is so vital to a realistic driving simulation, the peripheral field of view becomes as important as fine detail resolution. Unfortunately, there is a VR technical tradeoff between pixel density and field of view that is discussed in more detail below.

For cycling, the peripheral view is less critical because road speeds are significantly reduced. A flat screen mounted close to the eyes — say 15 to 20 inches — should replicate slow speed peripheral vision reasonably well.

Motion sickness

The greatest challenge by far in terms of widespread VR adoption is the tendency for many — perhaps half the population — to suffer various degrees of motion sickness, from serious nausea to mild dizziness. Precisely why this happens remains a medical mystery. Theories and remedies abound, and the closer VR gets to the optimal limits of the visual system, the less severe these symptoms are likely to be. But we are a long way from resolving the discomfort for those afflicted.

Surveys reveal that women are three times more likely than men to suffer severe motion sickness. Vulnerability appears to increase with age; those over 40 are twice as likely to suffer than those under 20. Headset technical sophistication (field of view and frame rates) may also play a role, but its degree of importance isn’t well understood.

The type of simulation matters as well. First-person shooting/walking games with a virtual body can cause disquieting mental conflicts. In general, sitting down in a fixed position is better than moving around a room.

Given all of the above, the first task of any serious VR exploration is to find out if motion sickness is an issue. Some mitigation is possible by taking breaks, limiting session time, and reducing simulation effects, but this quickly becomes counterproductive.

Key specifications

Technical specifications that generally define headset quality are:

1. display pixel density (higher is better)
2. field of view (up to 200° but tradeoff is visual clarity)
3. refresh rate (up to 150 Hz, the limit of human perception)
4. weight (less is better)
5. IPD adjustable range (51-77mm range is optimal)
6. degrees of freedom (post-2019 headsets incorporate all six DOFs)

Pixel density

Optimal pixel density would match the physical capability of the eye to process light, or its retinal (fovea) resolution of 60 pixels per degree of field (that is 1°). Density beyond 60 cannot be perceived by the brain at all.

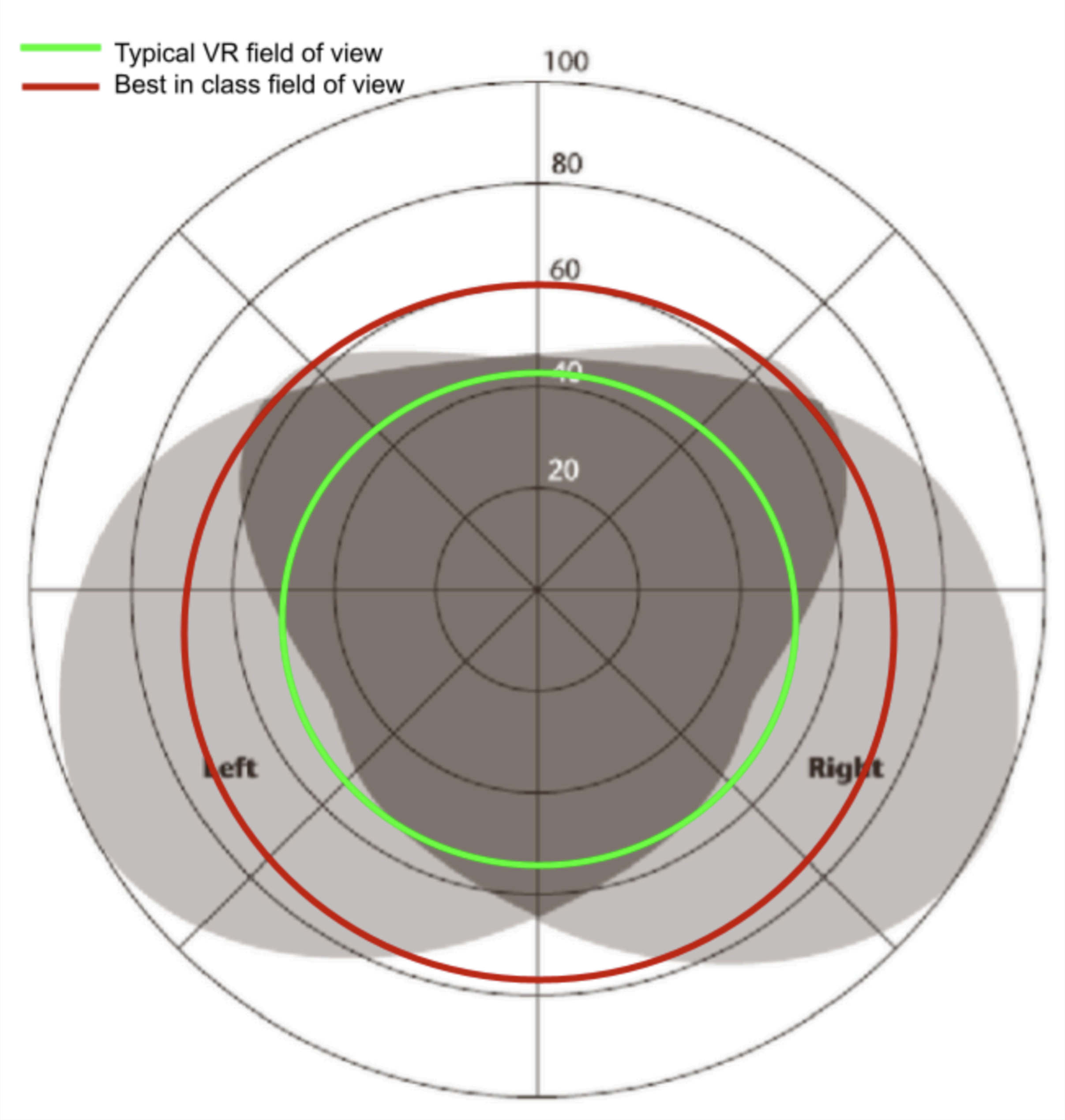
The highest headset density currently available is Primax's 3840 horizontal x 2160 vertical screen per eye with a 150° field of view. To convert this specification to the eye's resolution, we divide the horizontal density by the field of view: 3840/150, or 25.6. This is only about 43% of the optimal resolution of the eye, so we are less than half way to the optimal target in early 2021.

Compared to a 43″ 4K flat screen with 3840 horizontal pixels at the equivalent of a 100° field of view, the density of 38.4 is about 64% of retinal resolution. So a cycling simulation that places a 43″ flat screen about 15-18 inches away from the eyes is actually better than the very best VR headset commercialized in 2021 (refer to *Field of view* discussion below).

The highest defined technical standard in 2021 is 8K resolution, introduced in 2019, with a width of approximately 8,000 pixels — 7680 × 4320, or 34 million. The limit of human perception is about 9000 horizontal pixels (a future "9K" standard). The first 4K TV was released around 2012, so we can expect the next generation in 5-7 years, or probably by 2025.

Field of view

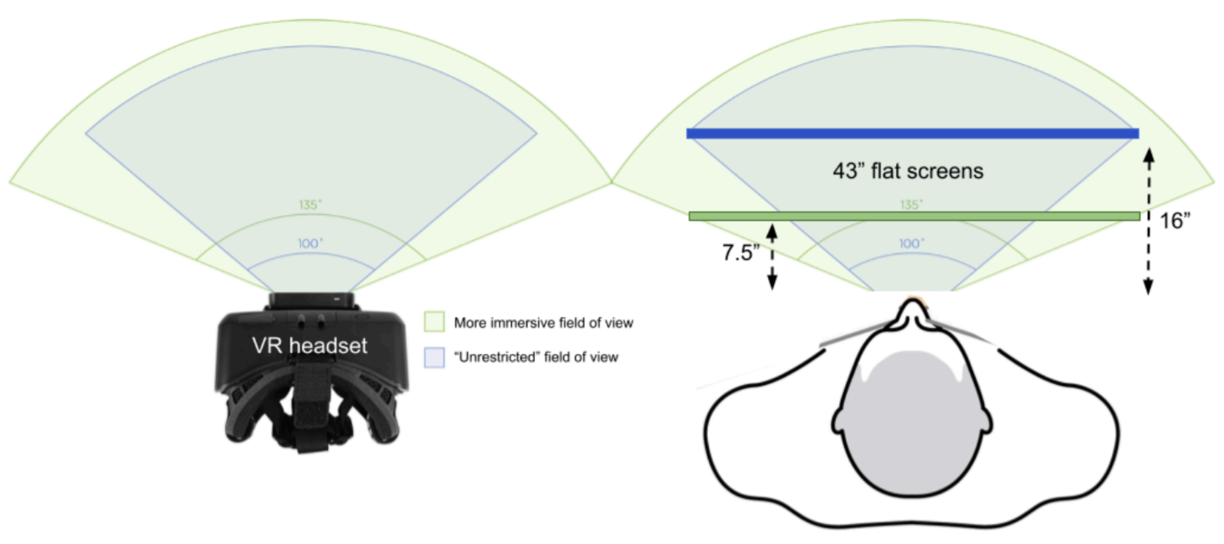
The human visual system has an overall 200° field of view using both eyes with a center focus area where the left and right eyes overlap about 110°.



Human visual field of view versus VR headsets

Since there is a tradeoff between pixel density and field of view, VR headsets tend to aim for the smallest field of view that isn't perceived as "restricted", or between 95° and 110°. As pixel density improves, field of view specifications will increase up to some optimal level. Recent research, however, suggests that reducing the field of view may help mitigate motion sickness.

While VR headsets are likely to penetrate driving applications with the next few years as technology matures, the indoor cyclist faces a different set of concerns about comfort. With the head sloped down and forward, the weight of the headset becomes extremely critical.



Headset vs. flat screen field of view based on distance

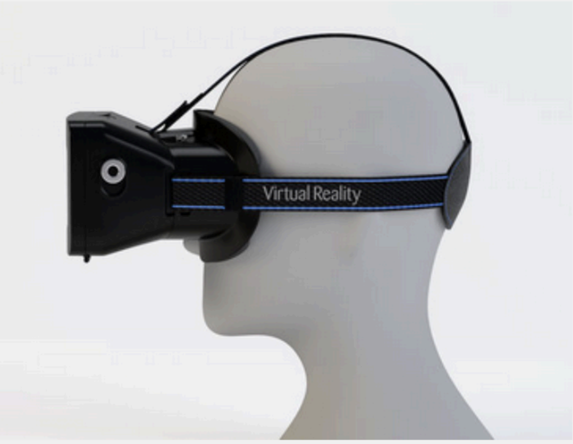
Placing a 43” flat screen, for example, about 16 inches from the eye results in a field of view approximately the same as a good VR headset. This distance is practical for stationary bike setups and eliminates the headset comfortable issue, as well as motion sickness.

Refresh rate

It is generally accepted that the human eye stops perceiving “flicker” between 60 and 90 Hz. However, recent studies suggest flicker sensitivity may exist even up to 150 Hz. Therefore, the maximum useful refresh rate is probably 150 Hz (the *Pimax 5K Super* uses a 180 Hz rate, the most of any headset). Most current headsets use 90 Hz rates which should eliminate nearly all flicker effects. Computer screens use a standard 60 Hz, just at the threshold of flicker-free perception which is why some people complain of screen fatigue, while the latest 4K TV screens offer 120 Hz or better refresh rates.

Weight

Headset weight becomes important especially with extended use.



Front-loaded headset

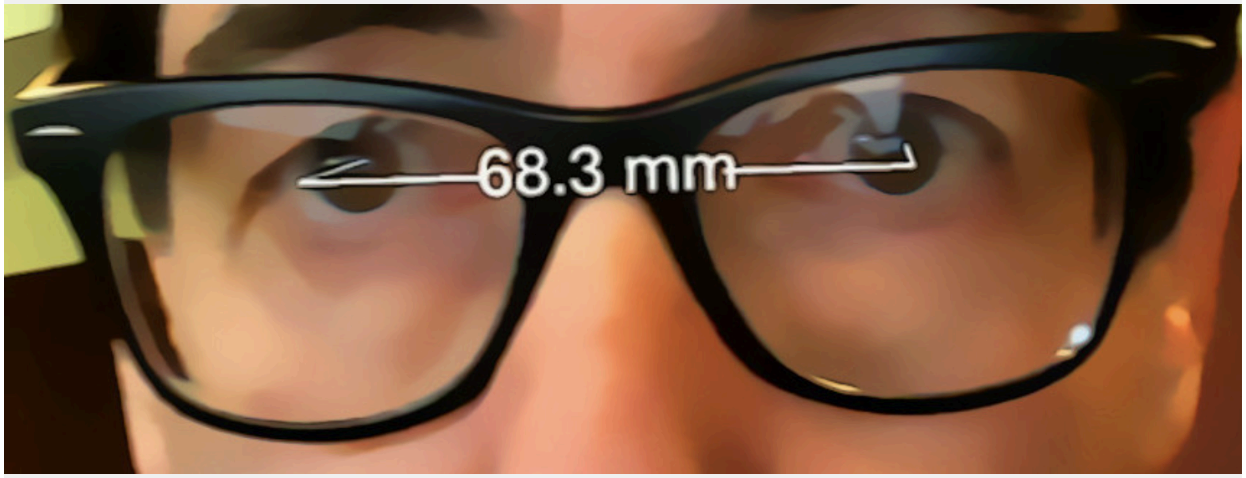
Unlike a racing helmet that weighs 1500 grams (3.5 lbs) supported by the entire head, VR headsets are significantly front-loaded, putting increased tension on neck/shoulder muscles and pressure against the face and skull.

The average VR headset weight is 600 grams (about 1.3 lbs). For comparison, a ball cap is 100 grams, while a thick frame pair of glasses comes in around 30 grams.

Products released in 2020-24 averaged 500 grams (1.1 lbs), still heavy for long sessions. Future development has a strong focus on weight reduction and distribution (so all the weight isn't on one's nose) in order to improve consumer acceptance. For example, Meta's latest prototype (codenamed "Puffin") weighs about 110 grams.

Interpupillary distance adjustable range

Interpupillary distance (IPD) is the distance measured in millimeters between the centers of the pupils, and varies in humans between 51 (small females) to 77 (large males). In binocular viewing that involves separate images for each eye, IPD becomes a critical design element for achieving clear vision.



Measurement of IPD using EyeMeasure iphone app

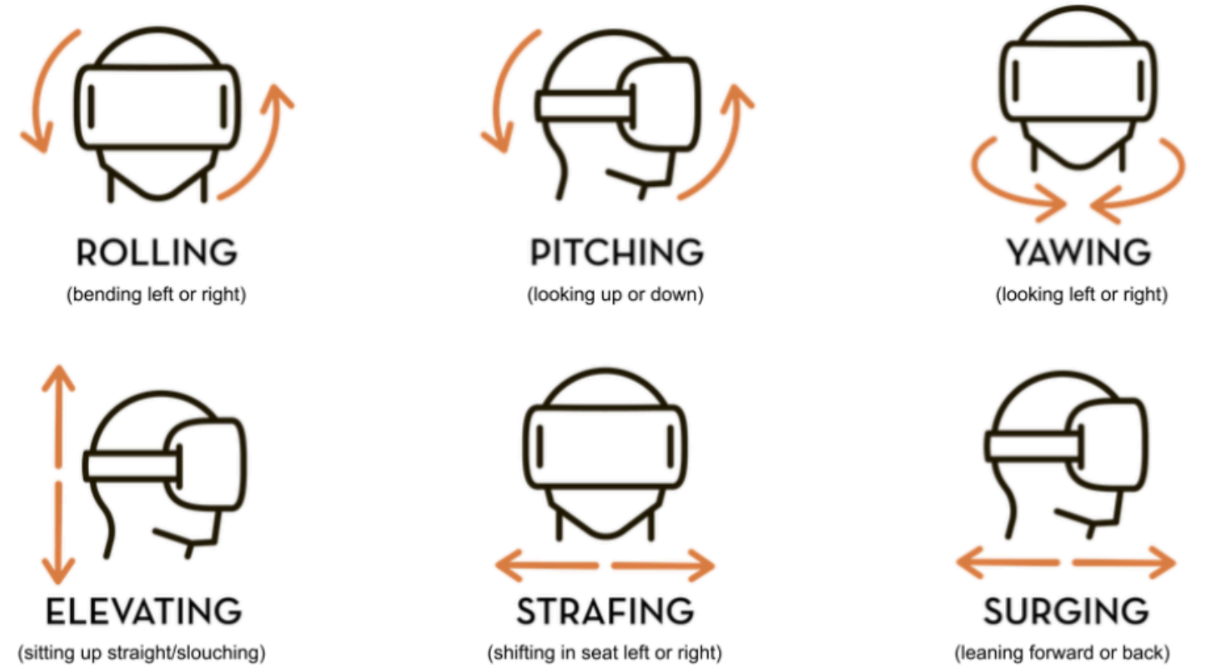
Early VR headsets had fixed IPD distances, causing problems for those outside of the "normal" range. Most current models have adjustments. For example, the popular *HP Reverb G2* has a 60-68 mm range.

Degrees of freedom

Recent research suggests that motion parallax cues impact both simulation realism and motion sickness vulnerability when conflicts arise between headset visual and extra-visual physical inputs like head movement. When we perceive that a distant object moves more slowly than one nearby, this is defined as motion parallax; it is a vital cue that helps the brain construct depth perception and works well even with one eye. Depth perception — the core of all three dimensional reality experiences — is a complex mixture of various visual and other sensory inputs, where motion parallax plays a significant role.

If the VR headset cannot translate head motion into what the brain expects given computer-generated parallax visual inputs, this conflict can result in physical discomfort. Exactly why some people seem to ignore these conflicts is a topic of intense research.

In any event, such conflicts can be significantly reduced by incorporating movement degrees of freedom (DOF) into the VR headset data flow. There are six possible degrees of freedom: roll, pitch, yaw, elevation (heave), strafe (sway), and surge.



Movement six degrees of freedom (DOF)

All six DOFs impact the perceived reality of the driving experience since the head is constantly in motion due to G-forces, road texture, and vehicle movement. Roll happens as the head compensates for G-force suspension shifts in a curve. Pitch is triggered by bumps or changes in road grade, and by looking up or down in the cockpit. Yaw is the common left and right head turns to check road and traffic dynamics. Elevation, in contrast, has a minor impact on visual perception and is mostly associated with uneven road surfaces (much more important for air pockets in flight simulation!), but may be experienced when shifting posture in a seat. Strafing (sway motion) is often present when turning left/right due to G-forces in combination with head rolling. The front/back surge of acceleration and braking is, of course, a very common element that must be accurately captured.

All in all, a full six degrees of freedom is a great improvement over just the basic three in terms of VR headset realism (and the prevention of motion sickness). Headsets released since 2019 have incorporated six degrees (6DOF) and this is now the minimum competitive standard.

Positional tracking

To achieve full 6DOF functionality, the sophistication of positional tracking has increased significantly over the past few years. Early rotational tracking (3DOF) relied on microscopic electro-mechanical gyroscopes to provide acceleration data from head movements that corrected position with dead reckoning algorithms.

HTC Vive Pro 2 base station (~$300)

In 2016, the Oculus Rift headset deployed infrared LEDs in a sensor base station design that has evolved into the "lighthouse" non-sensor marker-based system used by HTC Vive and others. Although the lighthouse configuration produces high quality tracking, it requires two wall-mounted base stations at an additional cost (around $300).

To overcome consumer resistance to wall-mounted base stations (often inconvenient in rooms that are not solely dedicated to a sim rig), an alternative tracking method with built-in headset cameras and computer vision *Simultaneous Location And Mapping* (SLAM) algorithms has been developed by Google, Facebook, HTC, Microsoft, and others.

The SLAM approach avoids a complicated setup with external base station mounts, but doesn't work well in dim light (which isn't an issue for VR headset driving/racing applications). However, the SLAM algorithms are complex and glitches can occur. In contrast, the external markers do not rely on algorithms and provide consistent high quality tracking data.

All headsets released since 2019 have “inside-out” tracking, either with marker base stations or camera SLAM (no external stations) tracking. In the 2021 class, only the HTC Vive Pro 2 (2021 Q2 release) uses external markers. As SLAM technology evolves, it is likely that external base station tracking will lose market share.

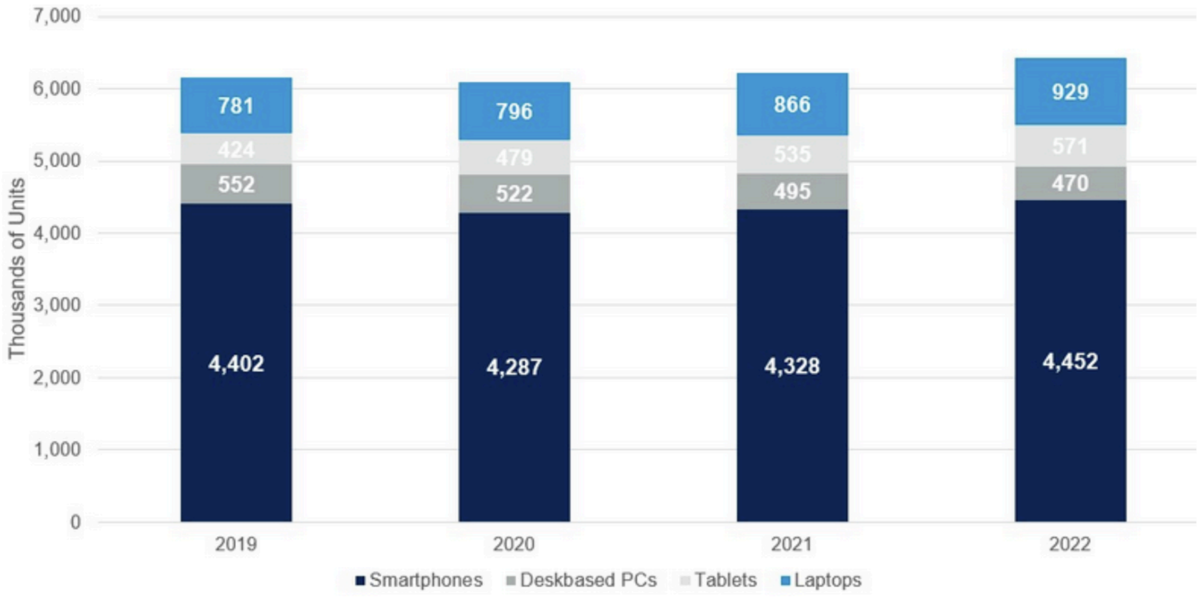
Price

In 2020, HP introduced the *Reverb G2* at $600 to good reviews and quickly captured a significant market share. Accordingly, it is unlikely that new products will enter much above that level. In fact, the upcoming *DecaGear* expected in mid-2021 has a preliminary price of $450. Downward price pressure is also exerted by Facebook who subsidizes *Oculus* ($399 MSRP for the *Rift S* model) in order to generate Facebook signups (use of *Oculus* requires a Facebook account). Average retail prices were $880 during 2019, probably the peak for this product category since 2026 prices have a current ceiling of about $600.

Given the speed of VR innovation, the useful life of a headset is likely to be only a few years. At price points around $500, manufacturers will anticipate 2-3 year replacement cycles much like smart phones and other consumer electronics.

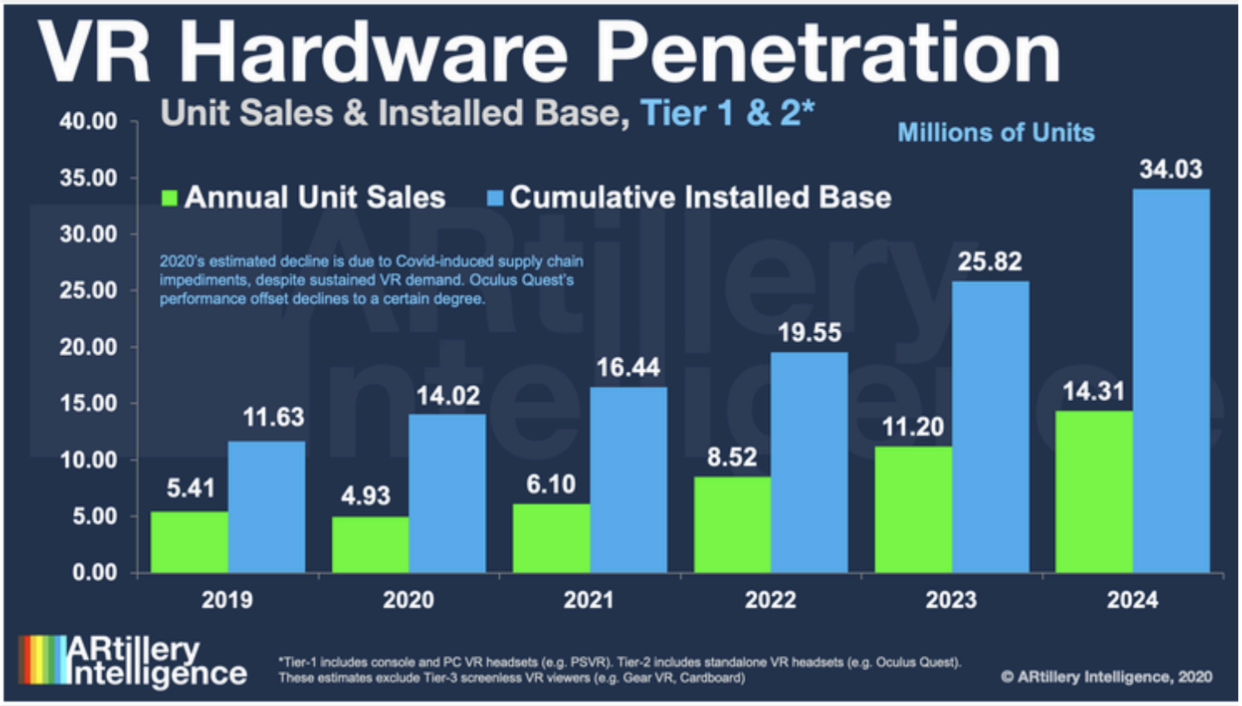
Product development outlook

An adoption curve analysis is helpful for understanding where we currently are in terms of VR evolution. Several common electronic devices have now reached global saturation levels that are reasonably stable.



Global installed base of selected electronic devices

The raw computing power required for VR will limit penetration to some fraction of desktop PC ownership, currently with a global installed base of around 500 million. Let's assume 45% of PC users eventually will adopt VR technology for various applications, suggesting a future installed base of 250 million worldwide.



2020's estimated decline is due to Covid-induced supply chain impediments, despite sustained VR demand. Oculus Quest's performance offset declines to a certain degree.

*Tier-1 includes console and PC VR headsets (e.g. PSVR). Tier-2 includes standalone VR headsets (e.g. Oculus Quest). These estimates exclude Tier-3 screenless VR viewers (e.g. Gear VR, Cardboard).

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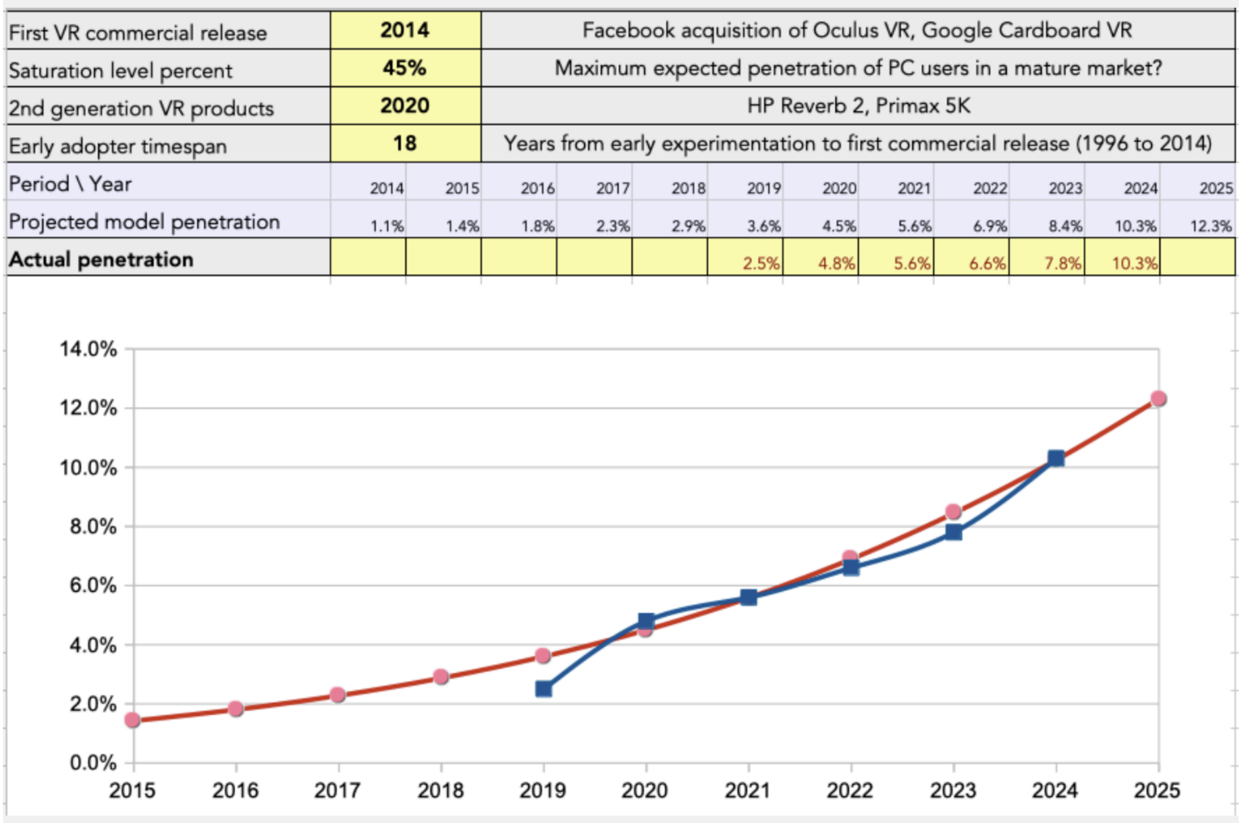
VR installed base forecast

Based on unit sales data (and assuming an ultimate 45% of the PC user base), we are now around a 6% penetration (15/250); fitting the *ARtillary Intelligence* forecast to a S-curve predictive model suggests that mainstream acceptance when 10% of the eventual market is penetrated will not occur until 2024. This transition typically signals the introduction of 3rd generation products that overcome key consumer barriers like motion sickness, comfort/weight, visual clarity, and field of view.



First VR commercial release	2014	Facebook acquisition of Oculus VR, Google Cardboard VR										
Saturation level percent	45%	Maximum expected penetration of PC users in a mature market?										
2nd generation VR products	2020	HP Reverb 2, Primax 5K										
Early adopter timespan	18	Years from early experimentation to first commercial release (1996 to 2014)										
Period \ Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Projected model penetration	1.1%	1.4%	1.8%	2.3%	2.9%	3.6%	4.5%	5.6%	6.9%	8.4%	10.3%	12.3%
Actual penetration						2.5%	4.8%	5.6%	6.6%	7.8%	10.3%	

Theoretical adoption curve (red) vs actual/ARtillary Intelligence forecast installed base (blue)

To reach mainstream consumer acceptance, VR headsets in 2024 are likely to have these specifications:

1. 8K pixel density or better that will eliminate "screen door" between-pixel distortions and deliver very high resolution detail
2. field of view of 150° or better for outstanding peripheral vision and speed perception
3. 150 Hz refresh rates that will eliminate remaining latency and flicker effects
4. weight under 400 grams with better head gear balancing to shift pressure away from eyes and forehead
5. full range of IPD adjustment
6. standard 6DOF
7. price under $750 even for premium models

In other words, the future looks bright.

Focus control

An interesting technology on the horizon within the next few years is *eye focus control* of computer interfaces, for example the NextMind device now available as a development kit. Using passive EEG (electroencephalography), a small reader placed at the back of the head picks up signals from the brain’s visual cortex and translates them into computer commands. This could be used to briefly enlarge side or rear mirror views (like a visually-triggered toggle switch) as well as offer other controls/effects that may be cumbersome to handle using physical hand or feet controls.

This technology could also alter incoming haptic, acoustic, or visual inputs depending on eye focus that may enhance immersion cues. For example, looking to the left side could briefly alter left speaker sound, change fan speed for wind effects, or impact some other part of the visual data stream. Glancing down at a dash instrument might trigger an audible readout like for RPM or speed, and if combined with verbal commands, a wide array of different effects should be possible.

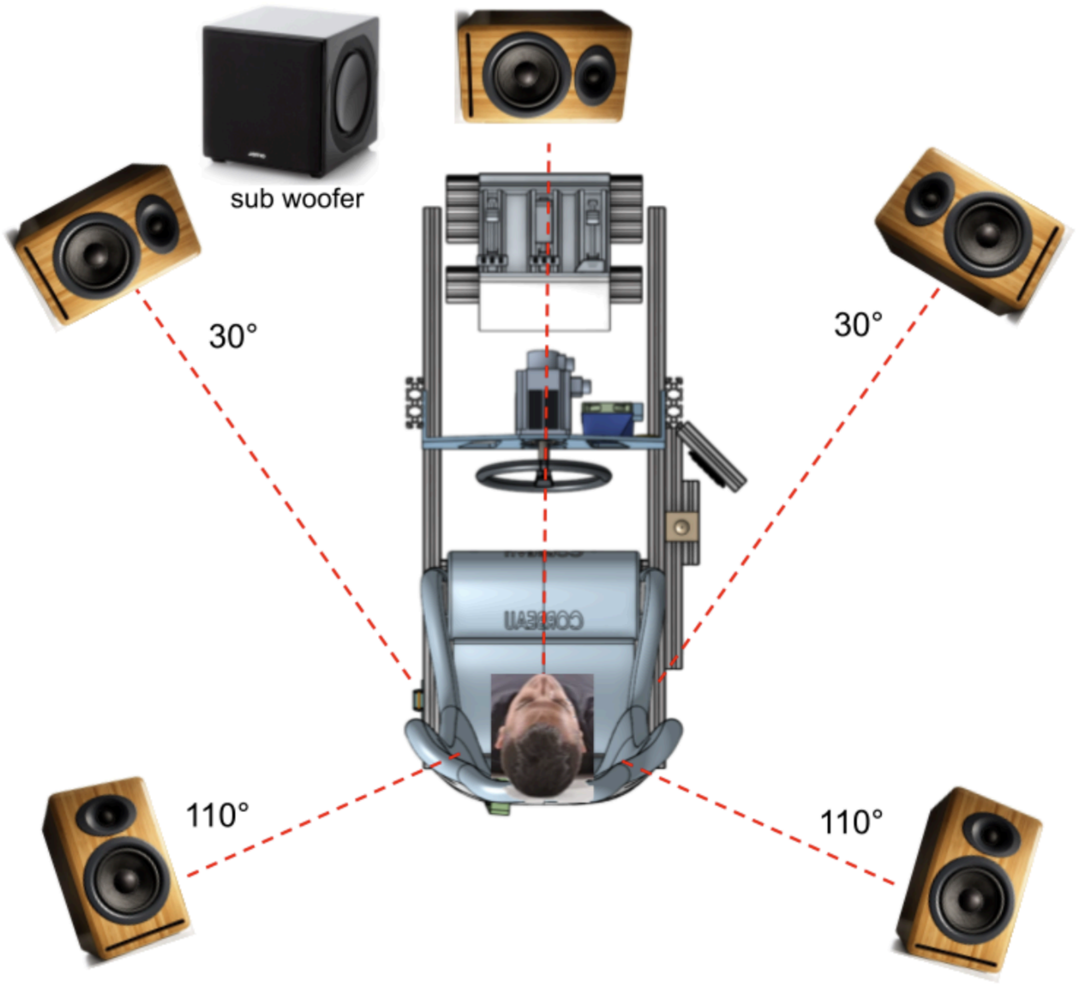
Focus monitoring may even present opportunities. For example, a lack of focus on the road ahead might aid a driving tutorial or, during a race, could produce an audible warning like ”curve ahead” or ”slow down”.

Hearing

The VR headset is bulky enough to limit the practicality of headphones that are not fully integrated. Most headphones are 300-400 grams which would increase overall weight on the head by 50%, well into the discomfort range especially for long racing sessions. So far VR headsets with integrated earphones do not provide a true surround sound environment and suffer from less-than-optimal acoustic resolution.

Surround sound

The current 7.1 sound card PC standard provides eight-channel surround audio commonly associated with in home theater configurations, but the older 5.1 standard is sufficient for a full immersive effect.



Optimal 5.1 surround sound setup for simulator

Five speakers are enhanced by a freestanding sub woofer for low frequency sound. When speakers are arranged in this manner, a full 3D environmental effect is possible. An additional subtle benefit of surround sound versus headphones is that the sound environment changes more realistically with head movement. For example, turning to check side traffic with headphones shifts the sound back (the traffic noise now appears to come from the rear, not the side) as modelled by programming algorithms. With surround sound, the acoustic direction does not change with the full immersive impact of a realistic 3D soundstage.

The surround sound setup is completely independent from LFE transducers used to simulate the feel of vibration.

Sound design

The three most important factors for immersive sound design are the quality of the soundstage, the playback audio accuracy, and the degree of visceral impact derived from feeling the sound rather than hearing it.

Soundstage

The soundstage defines the sound input data the helps us calibrate the width and spaciousness of sound to create a three-dimensional environment that reinforces our visual perception. In terms of immersion, this is absolutely critical since any breakdown in the "3D sound world" will impact the reality of what we see. Headphones by definition will always be severely restricted in terms of space and can never approach the richness of multiple speaker surround sound.

Proper acoustic tuning of a room is required to achieve the optimal 3D soundstage, and every room has its own challenges. All interior spaces suffer from naturally occurring resonance frequencies called room modes (or standing waves, eigentones, or eigenmodes) that are the primary cause of distortion and excessive bass "boominess".

Room modes are created when a sound wave travels between two opposite boundaries, for example the left and right side walls or the floor and ceiling. The first modal resonance occurs at the frequency where the distance between the two boundaries is equal to half a wavelength; for our 20 x 17 x 7.5 ft ceiling simulation studio this equates to 28 Hz primary (width) and 33 Hz secondary (length). The typical range of human hearing is 20 to 20,000 Hz so both of these modes are barely audible. Still they can muddy up the overall sound.

Mitigation of room modes starts with placement of the sub-woofer. Any location where the sub-woofer doesn't cause distortion from the driver seat position is acceptable.

After addressing room modes, the next variable is the level of reverberation or echo. The articulation of engine and road noise is improved if reverberation is limited as it naturally would be outdoors. Soft surfaces absorb sound, so a carpeted room is optimal. Low ceilings also reduce reverb and our 7.5-foot height is optimal. The hard wall surfaces can be modified with large picture frames that bounce sound waves in different directions, soft upholstered furniture, and textures like bookcases. If the room has windows (our simulation studio does not), these should be covered with heavy curtains. Reverb time is best if under one second and a room sound calculator indicates a rebound time of around 0.5 seconds in our simulation studio.

Background noise is the final issue to address. The computer, fans and sim rig equipment all generate noise that will generally be overwhelmed by road/vehicles sounds. Still high residual noise may be annoying and should be reduced if possible. Choosing a relatively quiet PC, for example, can make a noticeable difference.

Speed perception

Apart from its role in creating a realistic 3D world, audio input strongly reinforces the perception of speed through wind and tire sounds as well as environmental noises that change frequency due to the doppler effect as they pass by. Sound also provides vital cues about shift points when engine RPM and its related noise/vibration changes; note that this audio information is interpreted as sound via the ears and felt by the body as vibration.

Recent research outlines a novel cue to auditory speed perception: the temporal frequency of amplitude modulation (AM-frequency), typical of rattling sounds. Exactly what the underlying brain connections are remains uncertain, but acoustic quality at higher frequency appears to impart important aspects of speed awareness. This underscores the need for a high quality surround sound system.

Sound layers

Sim racing software often incorporates sound layers that isolate specific acoustic sources like engine, wind, tire, road surfaces, crashes, and communication. The volume of each layer can be adjusted so that important audible cues — ie from tire traction in a turn — can be clearly heard.

Communication

Verbal communication can provide important feedback about environmental and vehicle conditions and sim software typically provides an automated “crew chief engineer”. Third party apps like CrewChief increase feedback levels and can generate very accurate spotter comments — “clear right”, “hold line”, etc. — as well as expanded engineering information about car damage, tire wear, etc. CrewChief can also handle two-way communication via voice recognition to provide specific real time information on demand like tire pressure, lap time, who is leading/trailing, car gaps, overall race update, and so on.

Immersion is aided by real time two-way communication because it simulates the interactive community of an actual racing environment.

Indicator beeps

Due to high cockpit task loads during a race it is often difficult to keep a focus on the road ahead while simultaneously watching the tach for the optimal gear shift points. One useful enhancement is a sound generator that indicates RPM shift point levels.

Touch

Although no one can drive or cycle without vision, the experience also involves countless haptic (sense of touch) sensations. We encounter the torque force of the steering wheel in a turn, the tactile texture of the shifter, the grip of the seat and belt harness, the pressure of the brake pedal, and of course the gravitational forces (G-forces) that the vehicle's motion produces on our head and body. We also feel, rather than actually hear, the low frequency vibrations coming from the road surface and mechanical operations.

A fully immersive simulation must consistently convince the brain that the visual input is "real" by comparing what is seen to what should be felt as a result, and vice versa. The biggest challenge is pressure on the body caused by motion because a driving simulator, by definition, is stationary with very limited motions that can generate realistic gravitational or centripetal effects.

Motion forces (inertia changes)

Typical daily driver hard acceleration and braking generates G-forces of plus/minus 0.5, where 1.0 is the force of gravity in a free fall, or 21.93685 mph/sec. In other words, a 0.5 G-force implies a 0-to-60 mph time of 60/(21.9 x 0.5), or 5.5 seconds. A spirited race car might cut that time in half, generating G-forces of 1.0 or higher. A related force, defined as centripetal, is generated by any nonlinear motion, like driving around a curve in the road, even if the turn is at a constant speed. These effects can be calculated by:

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centripetal force = ([car mass] x [car speed]^2)/[turn radius]
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For example, entering a raceway turn with a 500 ft radius at 130 MPH in a 3,500 lb car generates a force equivalent to 2.3 Gs. Note that G-forces at a steady 130 MPH equal zero. So a typical race driver experiences G/C-forces well above 2.0 during a competition produced exclusively by turning, accelerating, and braking.

A critical fact about G/C-forces is that they persist during the entire event; a 6-second acceleration imposes a 6-second G-force on the driver. We experience these forces are pressure, either against the seat or restraining belt harness. The head is pushed by this pressure as well, so we feel added neck and back muscle tension, too.

There are three basic ways to simulate these forces:

1. tilt the seat platform (pitch and roll) so the body experiences a partial "falling or hanging" G-force that persists
2. jerk the platform momentarily to generate a small instantaneous force that does not persist

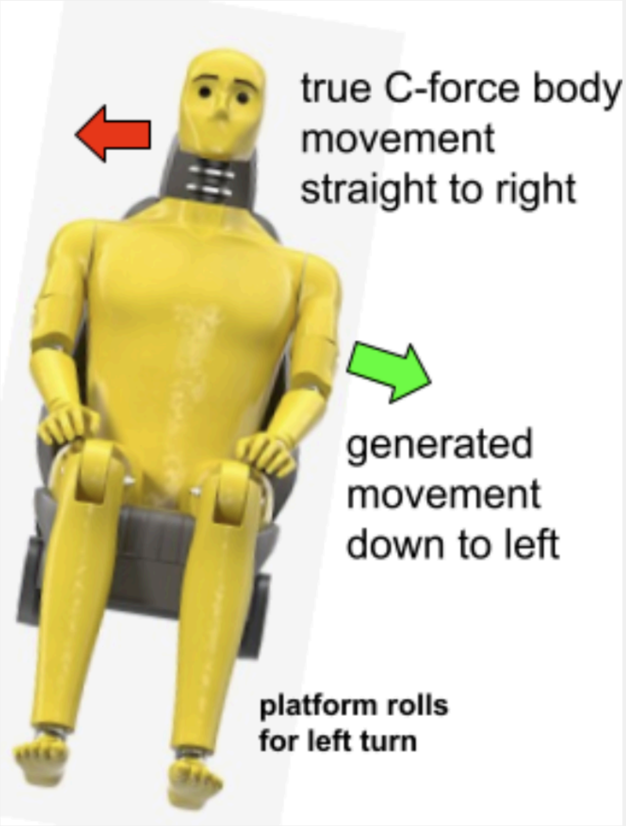
3. tighten/loosen the seat restraint to equal the expected strength of real world belt pressure that persists

These techniques only approximate true driving G-forces which *cannot be manufactured in a stationary environment*.

Seat platform tilt (pitch and roll)

How many Gs does tilt generate? A flat platform, of course, produces no “falling” pressure, just the normal feeling of gravitational weight. Assume a 3 x 5 ft platform can move 6 inches; this creates an incline angle of 5 to 9 degrees and equates to a “falling” G-force between 0.08 and 0.15, or the same as accelerating at 2-3 MPH per second … the same mild pressure felt during real world driving up or down a long hill. However, a platform pitch sensation of this pressure is *not* correct for acceleration/braking: tilted up instead of pushing straight back, and tilted down instead of pulling straight forward.

But what about tilting for turns? Here the story is more complicated.



Tilted platform in turn generates a faux pressure sensation

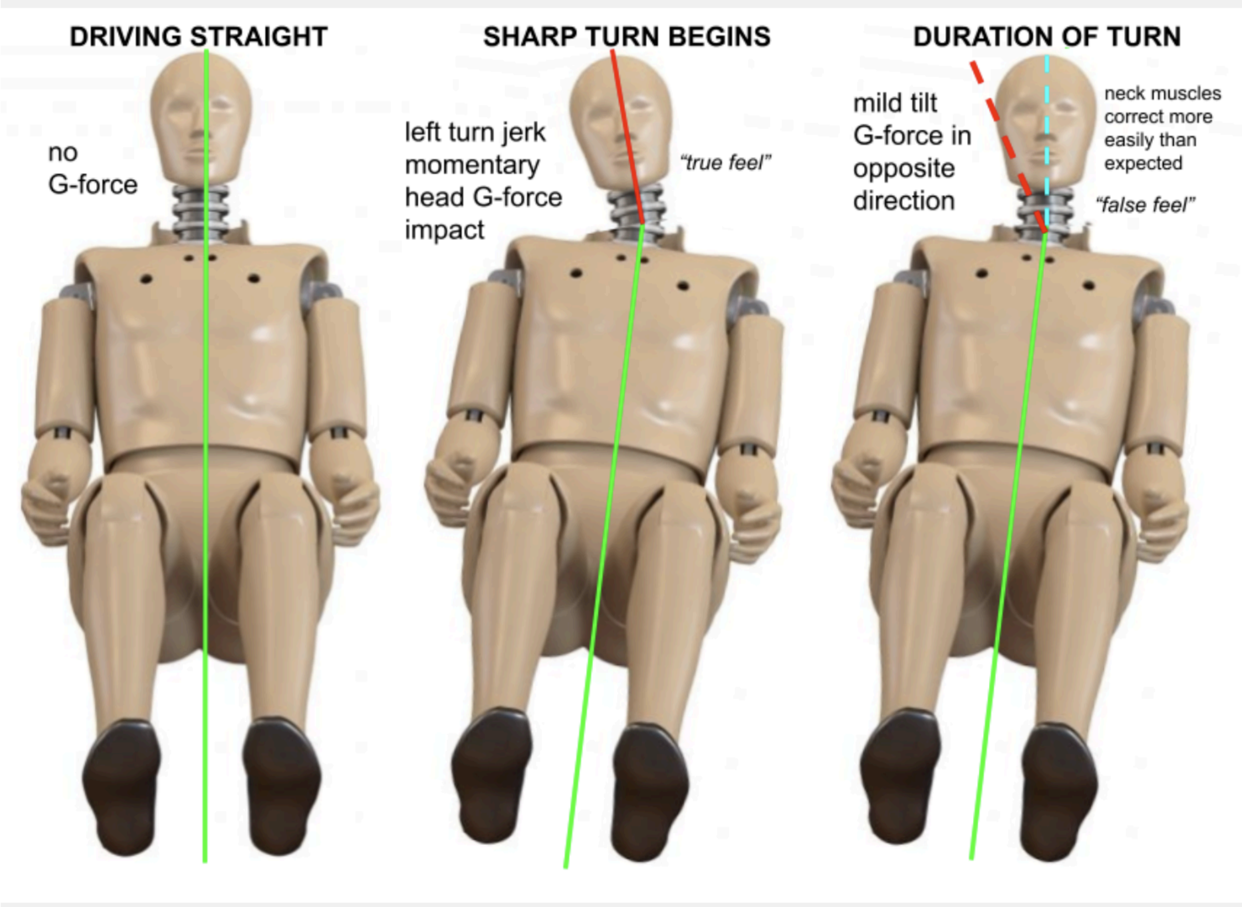
Tilting the platform in the direction of the turn (as the car chassis would move) seems intuitive. But the actual physics make this counter-productive. C-forces exert pressure away from the turn as momentum presses the body forward.

What we experience in real driving results in shoulder and neck muscle tension as the brain tries to straighten the head and adjust for the outward C-forces. A tilted platform, however, does the opposite: shoulder and neck muscles relax in the absence of real C-forces as the body shifts a little sideways.

For those not familiar with high performance driving, these subtle differences may not be noticed since everyday driving generates very modest G-forces leaving most consumers with no firm basis for comparison.

Instantaneous platform jerk

A quick jerk movement, either pitch or roll, does produce a momentary body response in the correct direction. The problem is that there is no persistent pressure as there would be in the real world.



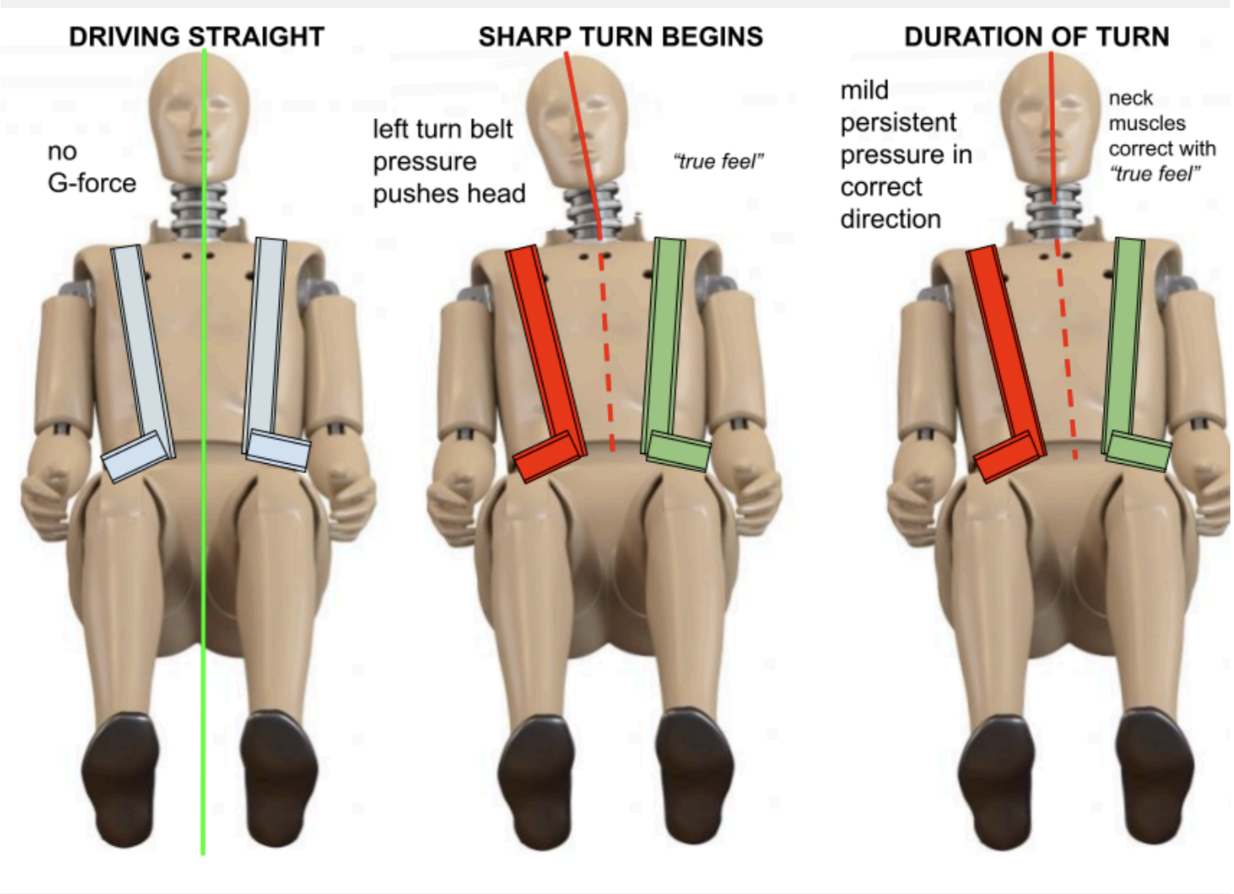
Platform jerk movement analysis

The persistence issue is pronounced in a tight turn because the expected forces are much higher, sometimes 20 to 40 times as much as the 0.1G of a platform tilt. A related problem is acceleration. What is the value of a split second acceleration jerk during a 10-second drag race? After the initial hit, there is no sensation that suggests continuing acceleration.

If our objective is as much realism as possible, the moving platform solution falls short on several counts although it may be a lot of fun.

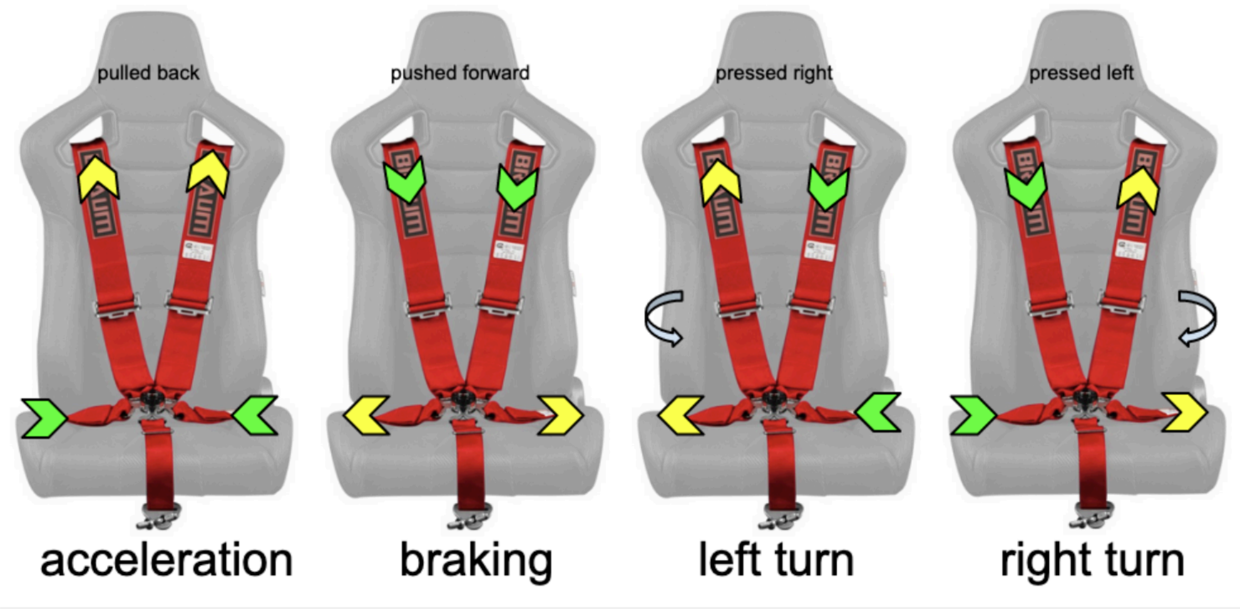
Active harness

The last possibility is to manipulate the seat belt harness so that the expected G-forces are delivered by belt strap pressure.



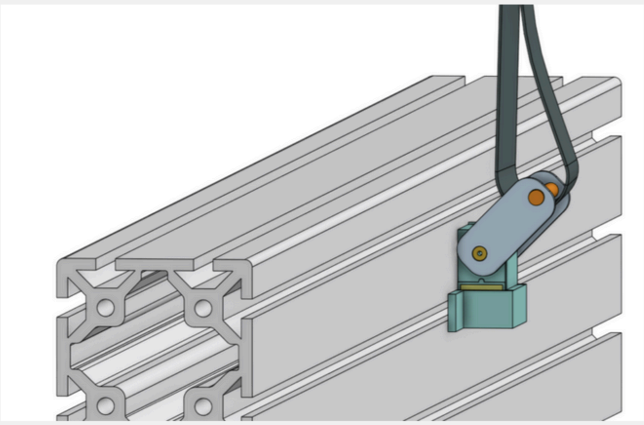
Seat belt pressure analysis

How might this work? In the illustration above, a red belt indicates increased tightening of the belt while a green belt is loosened pressure. The head is initially pushed in the correct C-force direction due to pressure on the shoulder and lower body around the waist. This pressure persists as neck muscles return the head to an upright position. Although the expected pressures are much lower than in the real world, they are in the correct direction.



Possible active harness pressures may simulate expected forces

An array of cues can be delivered; green arrows indicate loosening, and yellow ones tightening the respective belts.



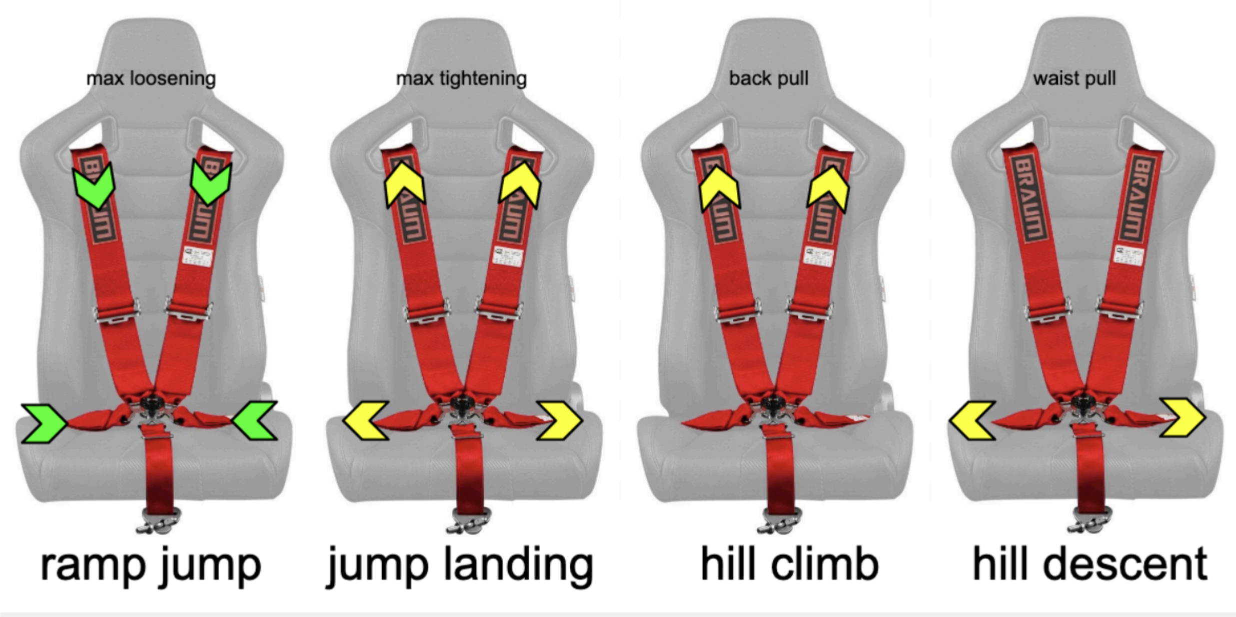
Will a servo mechanism for belt tension work?

By attaching four small independent servo motors to manipulate belt lengths, differential pressures may be able to enhance the intensity of VR visuals.

Low voltage servos with 25 to 60 kgcm torque specifications are readily available and may be sufficient to exert enough pressure for haptic cues.

Their small footprint permits mounting on 8020 rig profiles near the belt slots on sim racing seats.

In a similar manner, an active harness may be able to handle haptic cues for jumps and elevation changes.



Possible harness manipulation for jumps and elevation changes

Hopefully there are open source tools for programming that can capture a variety of belt manipulations triggered by racing game data.

Although motion systems are frequently seen as the ultimate step in racing simulators, an alternative method of G-force-like cues created by changing the pressures of a seat harness may just as effective at a significantly lower cost while avoiding platform movements that are subconsciously unexpected.

Constant speed

Linear constant speed generates no G/C-forces so both motion systems and active harness simulation techniques don't apply. As noted in our sight discussion, perception of speed relies heavily on visual cues, especially peripheral vision in a wide field of view. As speed increases, we perceive more wind and tire noise as well as higher engine RPMs typically associated with greater speed, a topic we will cover in hearing.

In terms of haptic cues, speed perception is aided by feeling — not hearing — very low frequency vibrations caused by differences in road texture and tire grip. In addition, larger chassis vibrations may play a role, especially on the steering wheel and shifter.

In an open cockpit car, wind velocity blowing over and around the head becomes important haptic data for the brain. Although closed cockpit vehicles generate no speed-related airflow, using carefully directed wind may greatly enhance the perception of relative speed and further reinforce visual information.

Bumps and vibrations

Apart from significant G/C-forces, driving generates continual jostling due to road bumps, changes in road texture, engine vibration, and transmission gear shifting.

Road bumps

The car chassis responds to uneven road surfaces through its suspension system. In the real world, this results in small but perceptible changes in vehicle *elevation* as springs/shocks absorb much of the impact on the tires but the entire chassis still moves up and down. A 3DOF motion system with four actuators on the corners of a movable platform can simulation this almost perfectly. In fact, the best feature of motion platforms is this unique simulation ability to mimic small chassis up/down changes due to uneven road surfaces.

If a motion system is not used, the alternative is low frequency transducers that can impart motion energy felt somewhat like up/down jostling. However, this vibration effect will fall short of the actual elevation changes and related small G-forces inherent in a motion system.

Vibrations

Simulated vibrations are best captured by the use of low frequency effect (LFE) transducers that can respond more quickly than moving actuators. For this reason, a motion system probably would also require a separate setup for transducers. In addition, a powerful surround sound system will produce low frequency sounds that are partly felt by the body, an effect that enhances immersion.

Tactile controls

Pedals, shifter, and steering wheel provide critical feedback as they control the car. Pressure on the brake pedal, for example, must correspond to the degree of deceleration. Likewise, turning diameter will generate different torque feels on the steering wheel. In addition to the correct feedback, the actual tactile feel of these controls is important so the design should mirror actual controls as much as possible.

Steering wheel

The steering wheel transmits a complex array of forces that are felt as turning resistance (or lack thereof) and road vibration. The source of these forces results from a combination of variables:

- turning effort from dead weight of front wheels when static (like moving the wheels when car is suspended on a lift)

- turning effort generated by gyroscopic forces from the mass of spinning wheels (like tilting a spinning top)
- tire effects caused by lateral cornering during a turn
- tire effects caused by longitudinal braking and acceleration
- suspension effects due to geometry of control arms and steering assembly

When driving it isn't possible to distinguish these variables individually; rather, they all combine to provide a "realistic" feel that must be mirrored with a force feedback wheel that can react quickly to telemetry and vehicle physics.

Shifter and pedals

The shifter and pedals do not directly respond to vehicle dynamics other than road and mechanical vibrations. While this makes it easier to simulate their tactile feel, there are subtle forces inherent to the mechanisms themselves that must be addressed for a realistic presentation. For example, the shifter must take an appropriate amount of effort to mimic the force needed to change gears. If gears slip, there should be a corresponding shudder to indicate grinding. Likewise, the brake pedal has a characteristic pumping resistance that increases as the brake calipers squeeze the rotor. All these controls can increase immersion if they replicate the expected tactile feedback of real world equipment.

Brake pressure

Simforge Mark-1 pedals from India

The brake pedal in particular becomes critical since its feedback pressure largely determines turning accuracy. For this reason, sophisticated pedal technology, although expensive, should be at the top of the equipment acquisition list.

Four pedal feedback methods are currently offered:

1. potentiometer control
2. hall effect sensor
3. load cell
4. hydraulic pressure transducer.

The brake pedal in a real car generates an increasing amount of resistance: the harder you brake, the more force you have to apply and in a race car, braking forces are much higher than in a typical daily driver.

Brake pressure realism generally distinguishes high from lower quality sets that exhibit more even pressure throughout the pedal's throw range.

As of May 2020, the Simforge Mark-1 pedals, newly introduced from India, offer very high quality load cell feedback technology at a price point in the mid-$300 range which is two to three times less expensive than comparable products. However, a lock down due to COVID has temporarily halted production.

Pressure transducer pedals are still extremely expensive and appropriate only for professional sim rigs.