



Recommended Practices for Automotive Haptics

Haptics Industry Forum | hapticsif.org

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2 Overview

Haptic technology is known to be a valuable tool for providing timely, salient feedback for interactive systems in vehicles. However, implementing haptics can be challenging because it requires careful design of a full stack of technology, ranging from electromechanical engineering to user experience design. Moreover, haptic feedback is highly effective when used for certain tasks, while being less suited to others. Understanding the potential and limitations of haptic technology will allow those who are designing automotive experiences to utilize haptics in a way that benefits users to the maximum possible extent while accounting for project constraints.

3 Who should read this document

This document is intended to orient product and program managers working in the automotive industry at OEMs, Tier 1, Tier 2, and Tier 3 suppliers who are considering adding haptic feedback technologies to their new or existing projects. This document collects together several decades of combined experience in this specific area by members of the Haptics Industry Forum. More information is available at <https://hapticsif.org/>

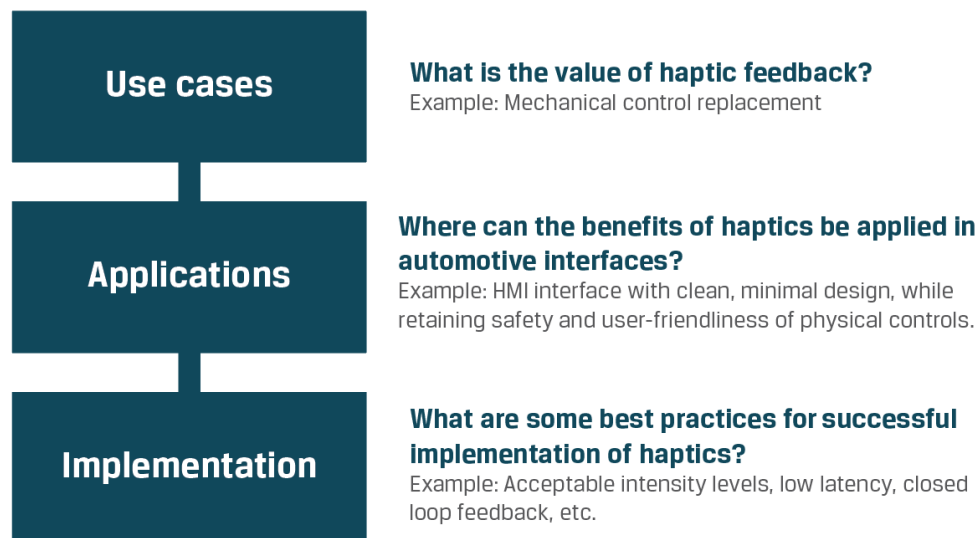
This document provides an overview of use cases in which haptics is known to provide meaningful added value to automotive interfaces. The typical integration process for haptics is described at a high level so that product and program managers can understand how haptics fits within a project plan. The technologies that are available for automotive haptics are described, as well as a list of vendors and providers. The hope is that this document will serve product and program managers well as a starting point for outreach and further research. Detailed technical integration and UX guidelines will not be discussed here.

4 How to use this document

The way to benefit from the value of haptic technology for automotive interfaces is to first understand what haptics offers to users of interactive systems. The known user experience value of haptics for automotive interfaces is discussed in the next section, entitled *Use Cases*.

Next, it's important to understand how this value manifests as a feature of an automotive product. This is discussed in the section entitled *Applications*.

Familiarity with best practices in the industry for instantiating that value through product design and development will ensure that haptic technology is utilized in the most efficient and effective way possible. To that end, the *Implementation* section begins with an overview of the haptic technologies that are mature and appropriate for automotive products and that are available today from suppliers. Integration guidance is provided, along with a sample workflow that lists the sequence of steps and decision points that product managers must typically follow when considering utilizing haptics in an automotive product.



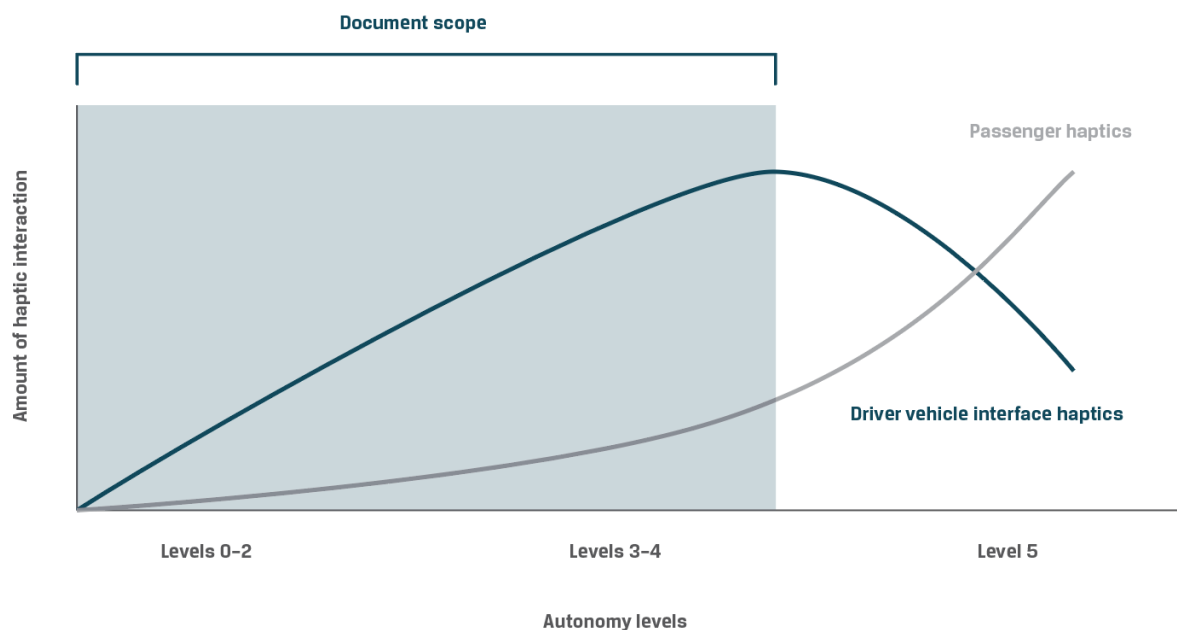
After these sections, a collection of representative case studies are presented to educate the reader about the features and functionality of in-market automotive offerings that utilize haptic technology. This is followed by a list of vendors who currently provide components, software, and other resources for automotive haptic technology.

After you have read this document, you will be well positioned to evaluate whether haptic technology is appropriate for your automotive application. You will have an understanding of the broad, collective automotive experience of experts in the field of haptics and will be empowered with a list of resources to draw upon to begin a haptic automotive project.

5 Overview of automotive haptics

Since the invention of the automobile over a century ago, the capabilities of cars have continuously evolved. Ongoing development of autonomous driving and electric motors is in the process of transforming the meaning of cars and the very act of driving. Today, the automotive industry can be viewed as a complex web of interconnected and intersecting technologies. The experience of driving is being radically transformed as the digital cockpit becomes instrumented with interactive surfaces, gesture controls, and immersive experiences.

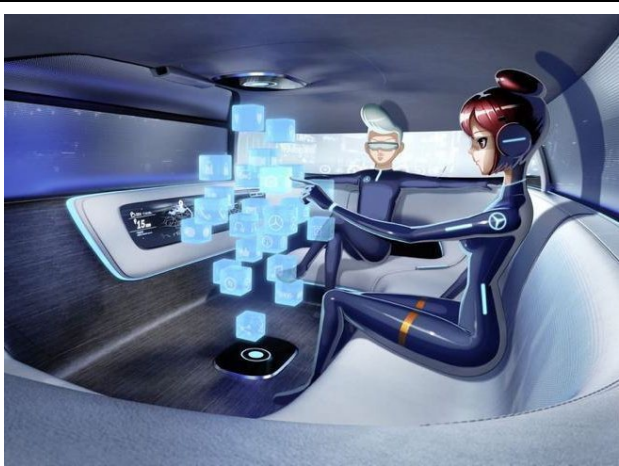
Automotive haptic use cases are dependent on the interaction models that are used in the car. While we may see the role of haptics change as cars become more autonomous, haptics will continue to have an important role to play. However, the role of haptics will likely shift from being focused on usability and safety for driving tasks to being a generalized technology for immersion and spatial computing for all passengers.





Today, haptics are integrated into the surfaces and displays of the car to provide tactile feedback, enhancing usability and safety.

Source: Immersion



In the future, a cabin with advanced haptic features will become a place for relaxation, work, immersive entertainment, and social interaction.

Source: Mercedes Benz Vision Tokyo

In today’s automotive products, haptic technology delivers two key values to the end user: usability and safety. To designers, it delivers industrial design flexibility and reliability. To brands, it delivers differentiation and branded experiences. As we move into a future where cars become more autonomous, the cabin will become a center of relaxation and entertainment, and haptics will increasingly serve as a part of the immersive entertainment system.

On the road to autonomous driving, display sizes are increasing, mechanical controls are being replaced with touch sensitive surfaces, and cabin interiors are being enhanced with new materials. And while car manufacturers aspire to create a comfortable, convenient, and immersive environment in the car, the primary purpose of an automotive cockpit is to support the driver in staying focused on the task of driving.

6 Use cases

This section describes the known value-added use cases for haptic technology in automotive products, in order of prevalence. At the end of this section, some speculative use cases are briefly described.

At the end of each use case description there is a list of key haptic design parameters that affect the quality and success of implementing the use case. The design parameters for haptics in automotive and the set of technologies that are required to control them are discussed in detail in the section titled [Implementation](#).

6.1 Touchscreen UI confirmation

The advent of touchscreens in automotive cockpits is changing the way people interact with their cars. Automakers are increasingly utilizing principles of design in layout, color, and interactivity, making automotive interfaces more appealing and user friendly than ever before. However, at the same time, the number of features that can be accessed on the touchscreen is exploding. With so many features available, drivers must be allowed to access these features while maintaining their attention on driving. Interaction design for automotive interfaces must thus minimize the amount of effort and attention needed from drivers to access various vehicle functions.



Source: Shutterstock

To ensure that the driver is always focused on the road and spends less than 2 seconds (NHTSA Driver Distraction Guidelines, 2010[1]) glancing away from the road to perform a visual task, haptics can help notify the user that an intended operation was performed. For example, with haptics, the user need not look at the screen while activating the climate controls to verify if it was turned on/off. By just adding the right design language, haptics will let the user know via a confirmation feedback that the requested operation has been performed.

With confirmation feedback, this allows the driver to concentrate on driving and reduce driver distraction. Confirmation feedback can be applied to any kind of touch surface allowing the user to operate the controls without looking. Latency is a key factor to take into account while designing for haptics. The user must be able to associate their actions instantly with the haptic confirmation that will allow them to focus on the main task of driving and not look at the screen to confirm their requested action.

6.2 Mechanical control substitution

It was the late 1800's when the automobile was invented in France and Germany before Americans began to reign over the automotive industry. Cars in the 20th century had a lot of physical buttons to control several functions within the vehicle. Model T was the first automobile created by Henry Ford for the common man. This vehicle was devoid of any physical controls. As the years progressed, the dashboard inside the car slowly began to evolve with more physical buttons and dials. Further along, introduction of knobs, cigarette lighters,

temperature controls resulted in an evolution that evoked a sort of fashion statement. There was virtually a clutter of physical buttons, dials, and knobs on the dashboard.

Source: Volvo



Source: Porsche

The new age of mobile phones catapulted the automotive industry to adopt a similar style to address what consumers were looking for. While physical buttons are good to have and control, over time these are prone to wear and tear resulting in replacement costs, increase in mechanical tooling costs, and making the whole design less flexible.

Auto makers began to look at minimalistic design while moving toward digitization that can quickly pave the way to make HMIs very customizable, flexible, and adaptable. This also aims to increase physical awareness of the surroundings and build a mental map of the locations of these controls. This is where haptics can also play an important role to deliver the user experience and maintain the modality of communication with the dashboard.

While replacing mechanical controls with digital or capacitive switches, the haptic feedback must be able to convey a button press with sharp, concise effects. This will help the user associate a button press/release

functionality. Magnitude is another design consideration to factor since it helps convey various meanings to the user to help differentiate key parameters.

6.3 Alerts

Alerts, a common use case for haptics in the car, are high priority notifications that aim to break into the driver's attention and provide critical, time sensitive information. Typical use cases for alerts include collision warnings, time sensitive navigation messages, and cues from driver assistance systems. The purpose of a haptic alert is to ensure driver's attention is on a high priority issue.

It is important to consider some of the design elements while implementing haptics for Alerts. One of the key requirements is Maximum magnitude. To indicate a high priority alert or in an event of impending danger, the haptic cues to the driver needs to be able to grab their attention and warn them quickly. Haptics can be designed with varying magnitudes and can quickly alert the driver with strong cues.

Another design consideration is Spatial differentiation. For example: Haptics can be used to warn the driver by creating vibrations on a specific side to indicate oncoming vehicles at a junction crossing. It can also be used to help the driver in navigation to indicate upcoming turns by sending vibration patterns on the specific side.

Scenario example: Collision alert during a morning commute

On a regular commute, the user while driving has a lot of things going on. Be it traffic, phone calls, kids, pets, family or other passengers, there are several factors that can cause the driver to be distracted. To counter the distraction, haptics can help in high priority notifications to alert the driver of any imminent danger. If the driver is driving too fast and doesn't realize the vehicle in the front has slowed down, by vibrating the steering wheel with haptic cues, it can warn the driver on time to apply brakes and slow down immediately. The vibrations on the steering wheel will alert the user of a Forward Collision Alert in a timely manner.



Source: Porsche Irvine

Design considerations

- Maximum haptic strength
- Location context, e.g., left vs. right
- Haptic effect feeling (sharp, abrupt vs smooth, rumbly)

6.4 Situational awareness

Having situational awareness means being actively conscious of your driving environment, such as monitoring the behaviour of other road users and pedestrians or factoring in environmental factors, for example. Haptic

effects aim to support situational awareness by providing information about the context of the driving task, such as road conditions and environmental factors.

It is becoming increasingly important with use of electric steering and drive-by-wire systems, tactile feedback for the driver has been reduced. Haptics can bring back driving feel for road and environmental conditions. For example, driving enhancement, i.e., haptic aspects of drive mode that can make the driver aware of their surroundings.

Situational awareness can be found in:

- Steering Wheels to provide user feedback for grip, surface conditions, traction, etc.
- Brake Pedal (e.g., ABS triggering, threshold for grip vs. slip)
- Seats to provide information about lane line crossings, collision alerts, and blind spot detection.



Source: Genesis

Another possible use case is to alert the driver of a lane departure. When the driver is driving at high speeds and doesn't realize the car is moving out of the lane without any intention to change lanes, directional haptics can be used to vibrate the specific side of the seat or the steering wheel to guide the user to move back into the lane. Magnitude, latency, dynamic range and audibility are some of the key design considerations while implementing haptics for alerts.



Source: Ford

Performance Driving

Haptic situational awareness is an essential element in performance driving. Traction, threshold braking and engine speed cues are critical inputs for a driver. References for performance driving haptics come from professional driving simulators, but will be covered separately outside the scope of this Automotive Haptics document.

Design considerations

- Maximum haptic strength
- Fine control of haptic magnitude over time
- Transient response sufficient to play multiple differentiable patterns
- Frequency control
- Location context, e.g., left vs. right
- Haptic effect feeling (sharp, abrupt vs. smooth, rumbly)

The difference between haptic cues for alerts and cues for situational awareness

A question that comes up when designing systems for situational awareness is, how does it differ from an alert? To explain the difference, let's take the example of a lane departure warning. This interaction could be designed to escalate the urgency of the message provided to the driver. First, the lane departure system notices a deviation from expected sensor values. The system activates a continuous haptic cue by vibrating the steering wheel. The intensity of the vibration reflects the magnitude of the detected error signal, and the location of the cue on the steering wheel indicates whether the lane departure is occurring on the left or right side of the vehicle. If there are no vehicles or hazards in the adjacent lane being entered, this situational awareness cue is all that is needed. The driver's comfort and focus are preserved. The driver may intentionally be changing lanes without using a turn signal. Providing a strong alert that breaks the driver's attention might actually introduce danger to the situation by causing an unnecessary startle reaction.

On the other hand, if there is a vehicle in the adjacent lane, a haptic alert may be more appropriate. This haptic effect would not support continuous awareness about the situation over time, but would instead be a strong and unmistakable haptic cue delivered fast enough to give the driver enough time to react. Concern for comfort and focus are secondary to safety, so rather than being designed to avoid a startle reaction, this haptic cue would be designed to induce it intentionally.

7 Applications

There are several application areas in a car where one can think of deploying haptics to. Listed below are some applications where haptics can help convey meaningful information.

7.1 Center information display

The Center Information Display (CID) as the name suggests is the central piece of the car that allows the driver to control a set of integral functions in the car. Be it functions such as Climate control, Seats, Navigation, or Media; these functions are the most commonly used during a commute. It is integral that the driver is able to access vital information on the CID without being distracted or spending time searching for these buttons.

CID comes in many forms with capacitive touch switches, digital switches or just a touchscreen as well. With the replacement of physical buttons with haptics, the whole personalization element makes the interaction with the user interface easier and more convenient. Haptics also makes it convenient with a redesign to the user interface. The whole user interface can be upgraded via software without having to replace physical knobs, buttons, or dials. Haptics enables the user to understand and realize that their operations have been performed, the command is recognized with a confirmation feedback. Haptics also enables the users to operate these digital switches safely and intuitively while focusing on the primary task of driving.



Source: The Verge

For example, a user while driving might want to perform a simple task such as turning on the radio or changing the media track on the touchscreen. There are many ways to perform this task, and one of the simplest ways to do this intuitively is to enable haptic feedback while operating the touchscreen. A confirmation feedback response for the operation performed helps the user focus on the road and avoid looking at the screen. Haptic feedback is meant to complement audio and visual feedback since the user might be distracted, and it is a necessary medium to enhance safe use of the car controls. There may be several reasons where an audio/visual response might be missed, or it may be a pure sensory overload. Enabling a touch response reaffirms the intent and enhances the user experience.

7.2 Trackpads & button panels

Car makers are deploying various types of displays to control entertainment and climate functions. These displays may be a mix of touchscreen and non-touch displays as well. To be able to control the functions on

your infotainment touchscreen, the user could either directly operate the touchscreen or use a touchpad to change the functionality or quickly access key features via shortcut buttons on the touchpad.

OEMs such as Mercedes Benz, Lexus rolled out touchpads in some of their vehicles to operate the infotainment display, quite closely mimicking how one would operate their smartphones. Haptics adds an additional edge here to promote safety. Operating the touchpad to perform the desired operation is accompanied with a haptic feedback to confirm that the action was executed. Trackpads offer the flexibility to operate a touchscreen without being distracted when accompanied with haptic feedback. Some trackpads even offer handwriting technology to input addresses for navigation.



Source: Mercedes Benz

Another application of haptics can be extended to button panels as well. Instead of having multiple physical knobs or controls, buttons to operate functionality such as heated seats or climate controls can be easily operated via haptic buttons thereby reducing clutter and also rendering an aesthetic feel. The interiors of the car are also changing rapidly with auto makers trying to use various materials for the cabin including wood, leather to extend a sophisticated look and feel to the car. There are some interesting smart surface haptic implementations that are expected to come in future models that include 'hidden capacitive buttons' that become visible as a user moves their hand over the surface. These buttons have haptic feedback when operated to confirm the user's actions but also disappear revealing the smart surface as it was before. This is a unique implementation to smart surfaces with a good user experience. Smart surfaces aesthetically look pleasing, reduce the number of physical buttons and can still render different functionalities that the driver of the car can access with a tap from their fingertips.

7.3 Steering wheel

The steering wheel is becoming more and more of a user interface for more than just steering. Buttons and other controls have proliferated in recent years allowing the driver to keep their hands on the wheel while adjusting volume or selecting a new streaming station. Today these interfaces include a variety of interaction elements including buttons, switches, dials but changing to capacitive button panels, touchpads and touchscreens. All of which benefit from the inclusion of haptics feedback in much the same way as they do for CIDs (above).

Another opportunity for haptics in the steering wheel is alerts. Since the driver's hands are a very sensitive part of the human body, alerts played here can be subtler than in some other locations. In addition, it is possible to provide more information than a simple alert, it is possible to play spatial haptics, that is patterns that provide more information. For example, with two or more actuators it would be possible to reinforce verbal directions with vibratory messages directing a driver to turn left or right and possibly an intensity, giving lighter or higher intensity as further information to the driver. In some use cases this could replace the verbal directions heard by the entire vehicle.



Source: Wheels.ca

7.4 Pedals

The feet represent another opportunity for haptic input for the driver. There are two key modes of feedback, vibration and kinesthetic feedback. The use of pedals can provide input to the user that meets several user needs, these include safety alerts, subtle suggestions, and drive feel.

The pedals are an ideal place for kinesthetic feedback, each pedal has its own use case. But the technology solution is similar. Kinesthetic feedback on the gas pedal can be used in several different reasons for different situations. First changing the stiffness of the pedal, this can be done for user preference but also in conjunction with other information the car has.

For example, as the car accelerates and reaches a cruising speed the pedal could be made stiffer encouraging the driver to slow down, similar to what has been implemented in the Nissan *Ecopedal*. As connections with actual road data increase this could be linked to actual road data like speed limits, or upcoming traffic or expected maneuvers like approaching your off ramp in traffic situations this could be used with collision avoidance systems to let the user know that acceleration at this time is not allowed. In addition, with many electric cars offering braking at the top of the gas pedal travel, kinesthetic feedback can help with ensuring the driver can feel this transition.

The brake pedal is another location where haptics can be used. With the use of electronic control much of the feedback to the driver has been lost, haptics can bring that back. One specific opportunity is to replace the feeling of anti-lock brakes in the pedal during breaking to let the driver know that the car is doing all it can to break. Kinesthetic systems could also make the brake softer when breaking is encouraged due to distance to car in front (before directly engaging) and other scenarios could make a stiffer pedal better.

Vibration feedback is easier to implement than kinesthetic feedback and can provide some of the same information. Warnings and alerts can be transmitted to the driver through the feet without noise or distraction to the passengers. In addition, with newer cars being quieter and producing very few natural vibrations, vibration feedback in the pedals can be used to engage the driver with a more exciting driving experience.

7.5 Seat

Despite the fact that a car is a confined space there is only one place that the driver is sure to be in contact with and that is the driver's seat. Therefore, the seat is an ideal spot for haptic interaction with the driver.

Most modern driver's seats already include a multitude of motors, and it is one of the places in a vehicle where space is also available for haptic actuators.

There are two very different obvious use cases for this location, alerts and massage. As the only location that is always in contact with the driver it is the ideal location for Alerts. Some cars already include lane departure warnings, but could also include driver drowsiness alerts, and confirmations, for the driver, that autonomous driving is engaging/disengaging. Each of these use cases can use distinct, recognizable patterns. For example, the seat could mimic the pattern of cuts in pavement used as a physical lane departure warning on many roads. In addition, the same system that delivered these alerts could also provide messages to drivers as a luxury feature.



Source: GM media

7.6 Hand tracking

One use case for hand tracking is gesture interaction which was first introduced to alleviate the visual distraction drawbacks that are inherent with touchscreen displays. Instead of locating a target on the screen and then physically touching the UI elements, users perform specific hand motions that are recognized by the system as dedicated control inputs. Gestures can be used to select and adjust features like the HVAC or Media controls; they can be used to handle system notifications as well as shortcuts through menus; they are also used for non-infotainment related tasks such as sunroof actuation. Despite allowing the driver to maintain their eyes on the road, this natural language interface lacks a sense of agency (the feeling of one's own control over their actions) due to missing feedback. Haptic confirmation can be used to provide tangible sensations that are paired with gesture interaction to improve agency as well as perceived responsiveness in the system. This also further reduces the need for the driver to glance at the touchscreen for a visual confirmation to their action.

As the industry moves towards higher levels of vehicle automation though, visual distraction becomes less of a concern and AR interfaces, such as full-windscreen Heads Up Displays and 3D Volumetric Displays, will likely become more prevalent. Elements within these become locatable through vision and interactable through

hand-tracking which also provides certain ergonomic convenience in not reaching for controls as well as hygiene benefits in shared environments. Yet aspects such as depth estimation during a hand motion will be improved through haptic feedback. When selecting UI buttons haptics can provide a tangible augmented reality interaction plane or confirmation feedback which supports accuracy and agency.



Source: Ultraleap

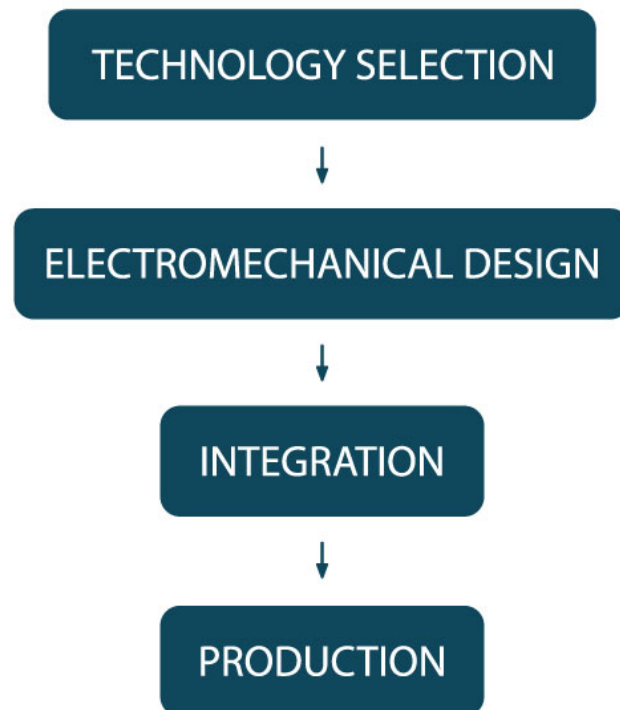
Haptic Technology	Vibrotactile feedback	Kinesthetic feedback	Ultrasonic friction	Mid-air haptics
Seat	Seat	Seat	Seat	Seat
Trackpads and button panels	Mechanical control substitution	N/A	Mechanical control substitution	Mechanical control substitution
Steering wheel	Mechanical control substitution	Situational awareness Alerts Mechanical control substitution	Mechanical control substitution	N/A
Pedals	Situational awareness Alerts	Situational awareness Alerts Mechanical control substitution	N/A	N/A
Seat	Situational awareness Alerts	N/A	N/A	N/A
Hand tracking	N/A	N/A	N/A	Mechanical control substitution

Readiness:

- Production ready
- Design win
- In market

8 Implementation

This section summarizes best practices for implementing haptic technology in an effective and efficient manner.



8.1 Technologies

Vibrotactile feedback

Vibrotactile feedback can be simply described as a form of tactile feedback on the human skin. One of the most important senses of the human body is 'Touch'. The sense of touch conveys information to humans. The skin is composed of various receptors that can detect vibration, pressure, texture, thermal, force, etc.



Source: Adobe Stock

Vibrotactile haptics is a type of tactile feedback perceived when an object is touched. This feedback is made possible by using electromechanical actuators. Meaningful information is conveyed via different modalities in the system such as pressure, vibration that can stimulate the skin receptors. These receptors can detect a wide range of frequencies from 50Hz-1KHz. Vibrotactile feedback exists in many devices today such as mobile phones, displays, seats, steering wheels, joysticks, etc.

This type of technology can be used for multimodal design that reinforce and complement design elements across visual, audio and haptics. Broadly, haptics can be used to convey different types of information as shown in the table below:

	CATEGORY	DESCRIPTION
	Confirmation Haptics	Haptics can provide the driver with feedback conveying that the intended action was performed. This can be applied to virtual button activation through simulated button clicks, or any other UI element.
	Information Haptics	Some information such as the status of a functionality (e.g. ON/OFF, Volume level, Fan speed) can also be delivered through haptic cues.
	Exploration Haptics	Studies have shown that haptic sensations proved to be efficient in eyes-free interaction; as such they can be used to help the drivers locate the UI elements they need to interact with, as to access certain functionalities.

The basic concept of vibrotactile feedback can be described as mechanical vibrations produced on the touch surface when an electromechanical actuator (Examples include DC motor, ERMs, Solenoids, Voice coils, Piezoelectric actuators) is excited at a specific frequency range.

The actuator is usually implemented as a resonant system (LRA for DC motors) or as a force source (PZT) when combined with the suspended touch surface that results in the user feeling the vibrations. Interactions of traditional UI implementations can be enabled with haptic feedback such as sliders, ticks, button clicks, textures, etc.

This technology can be used for a wide variety of applications across various touch surfaces including displays, seats, center consoles, touchpads, steering wheels, etc. In combination, this technology can work well to enhance auditory and visual feedback.

Choosing an actuator for the use case is an important step since this will aid the type of affects you can render, the type of driver required to drive the actuator, the number of actuators required to move the touch surface and the cost of implementation. There are several actuators available in the market today that can be used for several types of haptic applications in automotive.

Depicted below is an indicative table on the types of actuators available and the choice you can make depending on the use cases and applications you want to deploy.

Specs /Actuator	Solenoids	Linear Resonant Actuators	Voice Coil Motors	Piezoelectric actuators
Touchpad (100g)	✓	✓	✓	✓
7" Medium Touchscreen (250g)	✓	✓	✓	✓
10.1" Medium Touchscreen (850g)	✓ (Multiple)	-	✓ (Multiple)	✓
Large Touchscreen (<1Kg)	✓ (Multiple)	-	✓ (Multiple)	✓
Haptic Effects	Limited	Range of effects – Gradients, Textures, Buttons	Range of effects – Gradients, Textures, Buttons	Range of effects – Gradients, Textures, Buttons
Power consumption	Low/High	Medium	Medium	High
Frequency range	Moderate	Moderate	Wide range	Widest
Cost	\$\$-\$	\$	\$\$-\$\$\$	\$\$-\$\$\$

Note: ✓ indicates single actuator

Kinesthetic feedback

Kinesthetic haptics provide continuous, dynamic force feedback to the user. The technology has been a mainstay of the gaming world in gaming steering wheels, flight simulators and actual planes for decades. In the car the typical use case is actually in the pedals. Different techniques can be employed to generate the variation in feeling for the driver. This can include direct drive motors but that tends to be energy intensive, instead designs that allow the movement of pivot points altering the leverage being used or moving the end point of a spring to adjust its perceived stiffness are more common approaches. Use cases include adding more

force to a gas pedal encouraging the driver to slow down, simulation of the feeling of anti-skid activation. As well as allowing driver customizations where different drivers prefer different amounts of pedal stiffness.



Source: Adobe Stock

Surface friction modulation

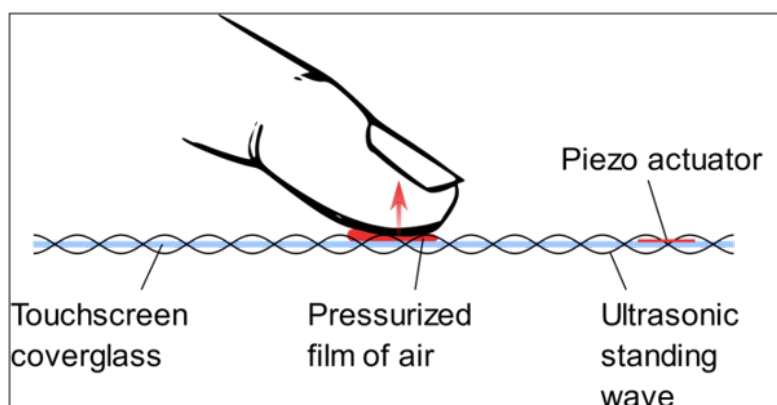
Surface friction modulation (also known as surface haptics) focus on modulating the friction coefficient between a fingertip and a surface, to create the illusion of a textured surface. It reproduces the frictional forces experienced by the finger when exploring a textured surface. Those forces induce strains and stretches which propagate on the skin, creating virtual textures.

Ultrasonic Lubrication

Ultrasonic lubrication consists of vibrating a surface ultrasonically, to reduce surface friction. Ultrasonic vibrations are imperceptible, yet the modulation of surface friction creates a texture effect below the finger.

The surface vibration is created using piezoelectrics actuators, bonded to the surface.

The technology is compatible with any rigid material (wood, metal, glass, plastic) and can be applied on a plane or curved surface, as well as on 3D shapes (cylinders, knobs ...). The 3D shape, applied on a flat surface, picks up on the haptic feedback emanating from the surface. Different effects can be applied simultaneously on different screen areas, allowing for multitouch interaction. Ultrasonic vibrations allow for extended capabilities, such as audio rendering and force sensing.



Source: Ultraleap

Ultrasonic lubrication allows for dynamic, customizable and reprogrammable user interactions. Each effect can be customized by the customer and/or the final user. New effects can be created directly by the customer. The main effects available are listed below.

- **Click feedback.** Static push effect.
- **Edge effect.** Distinguish different objects/area on the screen.
- **Virtual controls.** Create virtual sliders and virtual scroll wheels.
- **Texture rendering.** Wide range of high-definition virtual textures.

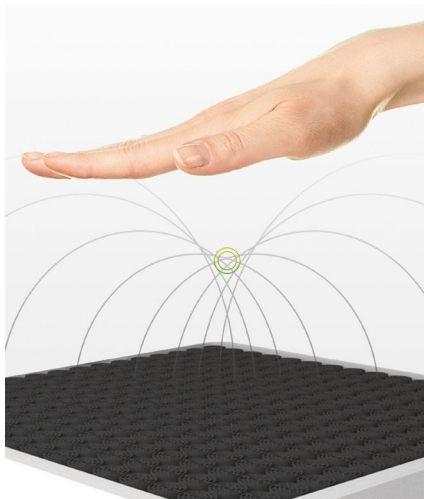
Electroadhesion

Electroadhesion haptic technology allows to increase the friction between a sliding finger over a surface as a function of a controlling voltage. The modulation of such voltage as a function of the user movements allows the creation of texture feeling and UI elements while interacting with an automotive screen.

The functioning principle of electroadhesion relies on the generation of a polarizing electrical field between the screen surface and the human skin. This electrical field increases the amount of compressing force contributing to the frictional resistive force which is perceived by the user. Electroadhesion achieves the generation of a polarizing electrical field by inducing a small current within the human skin which is harmless and not perceived by the user between two inversely polarized areas of the screen.

Ultrasound (Non-Contact)

Ultrasound devices are used to generate haptic sensations by creating variable pressure volume in the air over the ultrasonic transducer's surface. The variable air pressure generates a perceivable effect on the human skin that can be modulated to generate intricate tactile experiences. The devices are known to generate light sensations which can be perceived simultaneously when the human body hovers over the ultrasound transducers. These devices, therefore, do not require specific wearable or contact with a physical surface.



Source: Ultraleap

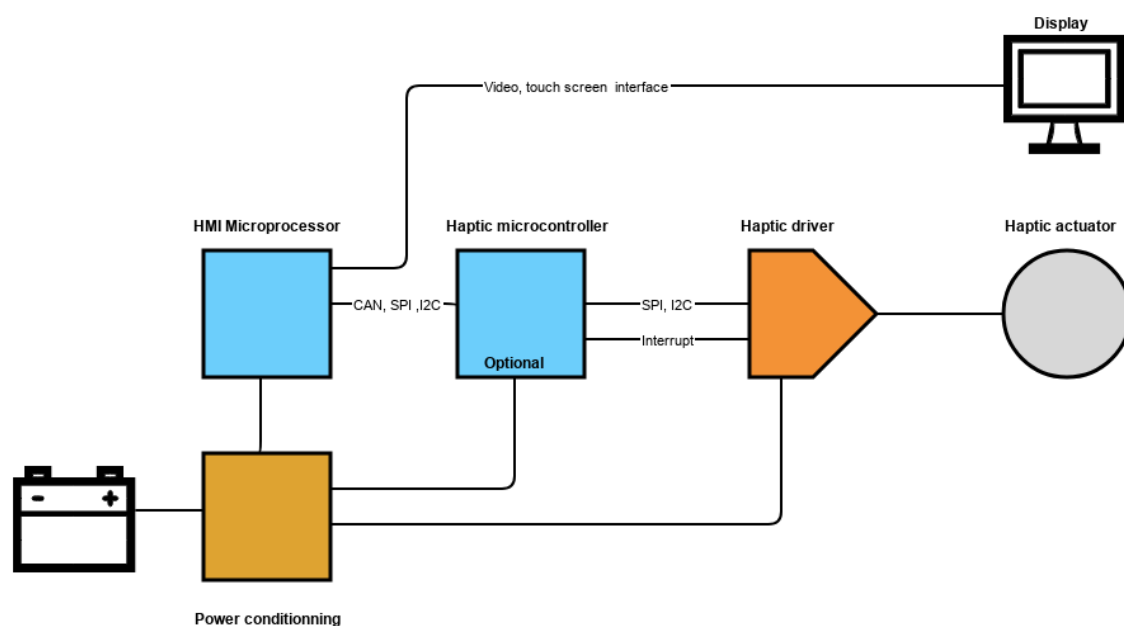
8.2 Software best practices

A good piece of software is key to improving the user experience. However, software alone will not complete the user experience. Software needs to work in conjunction with hardware and other parts of the system. One of the first examples that comes to mind is Latency. Latency plays a very important role, especially when we speak about haptics. Software comes into play when you really think about rendering haptic effects. There is control signaling, control software involved at firmware level, and this impacts on how the hardware works. For example: When you touch something, you need to feel it immediately which leads to the key requirement of low latency. The weighted hardware and software work together to both detect the touch and then play back haptic effects. If the latency is really high, i.e. a gap of more than 80-100 milliseconds between touching

the surface and feeling the effect, it results in a cognitive dissonance in your brain where it doesn't feel right, and your brain will disconnect the two things from each other associating the haptic effect to something else. Of course, like all technologies, with poor hardware choices or bad implementation, haptics may not necessarily address or serve the need. For example, the strength of haptic feedback may not be enough to provide notifications to the user. This could result in driver distraction causing them to focus on completing the task they intended to. Another reason could be about introducing haptics very late in the design process. This may not result in a good system performance or may affect other operating parameters which need to be worked out at the initial stage of designing. Complementing other forms of feedback such as audio will help notify the driver of completing the intended operation.

8.3 Electrical engineering best practices

Along with software and mechanical design, electronic design is one of the three key areas that will influence the haptic system performance. In order to provide the best possible experience to the end-user while minimizing cost and accelerating time to market, a set of best practices must be taken into consideration.



Source:

Architecture

Working with UI/UX and mechanical designers, quickly define how many actuators will be needed to achieve the desired haptic feedback. How strong these actuators need to be? Do they need special driving circuitry? What is the haptics frequency range required? You will also need to clarify if haptic force sensing is required and, if yes, what the level of force sensing uniformity required? Working with software designers, you will need to see how the haptic actuators will be driven and if any real-time support from the HMI subsystem is required. Often, actuators will require complex waveforms that must be generated in real-time. Haptics force-sensing could also require real-time processing to provide low latency and accurate feedback to the end-user. Depending on the HMI processing load and its ability to respond to real-time processing needs, you may want to consider dedicating a microcontroller to the haptic subsystem. Alternatively, some actuator drivers offer functions that will help reduce the latency by relieving the HMI processor from low-level real-time tasks.

Component selection and design

Once the system architecture is defined, the next step will be to select the required components and move on to design. Many factors will influence your choices, but here is a list of the questions you should ask yourself. What is the system budget? What is the power budget? Can the electronic component manufacturers provide long-term availability? Can they offer automotive qualifications? What is the level of reliability that is required? What will be the operating environmental conditions (temperature, humidity, vibrations)? What are the applicable EMC and safety standards?

Production and maintenance

You will also need to work with your manufacturing team or subcontractor to ensure your design is manufacturable and that a high production yield can be achieved. How will you test the haptic system? Can testing be fully automated? What will be the test coverage? You will also need to think about in-field maintenance. Can the haptic system provide self-diagnostics? Can the firmware of all subsystems be updated in the field?

8.4 Mechanical engineering best practices

Vibrotactile

While designing haptics for the system, it is important to consider the mechanical characteristics of all the moving parts that constitute the floating mass. In order to have good acceleration distribution and low sound level, the floating mass parts should not have any mode of vibration within the haptics frequency design range. The ground mass needs to be designed at least 10 times higher than the floating mass and needs to be a rigid structure.

It is also vital to have a good mechanical suspension designed in case of vibro tactile haptics implementation. A bad suspension design can result in a lot of uneven vibrations and noise. The overall result will not be pleasant and can lead to a bad user experience. The suspension design should provide one single degree of freedom in the direction of motion and have its natural frequency within the haptics frequency design range.

A highly damped system may reduce the acceleration. The suspension needs to be rigid to prevent unnecessary noise from being transmitted. A frequency modal analysis on the suspension design is integral to identify other modes of vibration that could interfere with the haptic frequency range of the device.

The other factor to take into consideration is the mounting of the actuator. The position of the actuator on the suspension and the surface being vibrated also plays a key role. When the human finger presses on the surface, the haptic sensation needs to be consistent. Not mounting the actuator correctly can weaken the haptic perception. One may feel different strengths as they traverse the surface. Typically, most interactions are vertical or horizontal with respect to menu navigation.

Ultrasonic lubrication

For ultrasonic lubrication, the key parameters are based on the mechanical response of the screen. As a matter of fact, in the ultrasonic frequency range the wavelength being of the order of the screen thickness, complex acoustic responses can be obtained due to the multilayer structure of the interface. Furthermore, soft layers (such as OCA or polarizers) exhibit non-linear mechanical responses as a function of the amplitude and frequency of the ultrasonic excitation. Thus, the first step in implementing state-of-the-art ultrasonic haptic feedback in a display is an advanced acoustic study. This will feed into the models used to optimize the design of dedicated piezoelectric actuators. These actuators will efficiently generate standing ultrasonic waves to provide homogeneous haptic feedback over a large area.

Ultrasound (non-contact)

Multiple transducers can be placed over interior surfaces of the car to suit the architecture of the customer. For these bespoke arrays, a fibonacci spiral arrangement of transducers is recommended over a rectilinear arrangement to reduce grating lobe effects. Grating lobes are spurious sensations and can have a detrimental impact on sensation lucidity. The number of transducers used for an interface array will impact the field of interaction too. Target usage should be considered when deciding upon array location as the packaging space will dictate the power with which the haptics are felt within an approximate 80cm height above the array. The more transducers compacted onto a surface, the more powerful the sensations will feel at the upper reaches of the interaction zone.

Cost and BOM optimization

Performance and cost are often related, and such is also the case in haptics. Therefore, before actually starting a cost exercise one must already have established a relatively good viewpoint regarding the targeted performance level, which de facto often becomes challenging to establish before actually having built and experienced a first set of functional prototypes.

Furthermore, haptics being a multidisciplinary system it's important to acknowledge not only how the various components impact on the performance, but also which components work particularly well together, and which component combinations are best suited for which application design.

Consequently, because of its multidisciplinary matter, it's difficult to compare costs of various haptic components with one another, as e.g. changing the system's haptic actuator will most probably influence other parts of the solution, i.e. one may be able to save costs on the actuator but due to a different actuator increase the costs of the driver (or mechanics), or in the worst case end up with not achieving the targeted performance.

Eventually one will more often than not end up in an iterative process, where fine tuning of small technical details may have a big impact on the user experience (i.e. latency, haptic strength or reducing unwanted sound).

Hence, when optimizing a haptic system, it's important to remember the following guidelines:

- Plan enough time for iterations, it's never first time right
- Within haptic solutions there isn't a one fit all technology
- Firstly, define your targeted performance, by building prototypes
- Secondly, prepare to reach cost down and performance targets by iterations, when having understood the full solution and each components impact, both on cost and user experience

In a haptic solution all disciplines are heavily connected, often requiring several small iterations to reach the targeted performance, BOM and thereby costs. The components that form a part of the haptic solution can include:

- Driver Hardware i.e., Amplifier
- Actuator
- Mechanical suspension
- Microcontroller that hosts the software
- Force/Pressure sensor

Quantification of Haptics

We are not talking about "Designing of Haptic Feedback" at this point, but about the evaluation, specification, and quantification of active haptics. These are the key parameters:

- **Transient response.** The speed with which a haptic actuator can respond to a signal. A fast transient response enables shorter, crisper effects that remind people of mechanical buttons.

- **Audibility.** The audio content of the haptic system includes both intended and unintended audio. When designed intentionally, the audible component of a haptic actuator can complement the haptics, but unintentional audibility of a haptic actuator can detract from the user experience.
- **Maximum magnitude.** The maximum acceleration (peak to peak) magnitude of touch sensation that can be produced by the haptic system. Magnitude must be high enough to overcome the baseline vibration of the cockpit due to movement as well as the ambient audible and visual environment which detracts from tactile sensitivity.
- **Dynamic range.** The number of distinct levels of magnitude that a haptic system can produce. Haptic effects may be made distinct from each other by designing them to be perceived as having different magnitudes. (? magnitude or frequency range? from Neil)
- **Latency.** The time that elapses between two sensory modalities (e.g., a visual effect and a haptic effect), or the time that elapses between an input (e.g., a gesture), and a haptic response. Low latencies ensure that users can interpret the haptic output as relating to their input. Higher latencies can make controls feel heavy, or if too high, unresponsive or confusing.
- **Body locus.** The location on the body to which a haptic effect is presented. Targeting a haptic effect to a specific body part helps the user understand the context of the interaction – for example, co-locating a haptic effect with the touch input that caused it creates an intuitive feedback response. Conveying haptic effects to different locations on the body can also be used to present directional cues.
- **Frequency.** The frequency in Hertz (Hz) of a vibration intended as a haptic effect. The feel of a low frequency haptic effect might be described as dull, round, or fluttery. The feel of a high frequency haptic effect might be described as sharp, clicky, or mechanical. Frequency can thus be used to express the brand behind a haptic interaction. Frequencies that are different enough to be perceived as distinct from one another can convey meaning or additional information about an interaction. (? Do we have link to a more detailed doc? from Neil)
- **Sensor trigger threshold.** The sensor output value that is used to trigger a haptic event.
- **Normalized energy transfer.** Haptic feedback is fundamentally "subjective". However, to compare different haptic signals with each other, the intensity must be calculated. This number is calculated from the measured acceleration curve of haptic feedback by filtering according to human perception (above 50 Hz and below 300 Hz).
- **Efficiency of semantic transfer.** Humans have the ability to infer semantic information through haptic feedback due to a variance in spatiotemporal parameters; therefore, it is possible to create tactile icons for different functions. Whatever the context, haptics should be evaluated for the appropriate meaning they convey to ensure the desired effect is achieved. This can be done through human-perception multidimensional scaling studies whereby a subject is asked to match a stimulus to a list of interpreted meanings.

The biggest challenge in the quantification of haptics is certainly to consider the complete application. Not only the technical specifications of the actuator (especially piezo and electromagnetic).

In automotive Tier 1, many are familiar with the specifications of mechanical switches (S-curve). However, active haptics require different parameters.

The following parameters are relevant for the quantification of active haptics:

- Type of haptic effect, such as custom designed effects, effects from a library, gesture-in-the-loop effects, and so on.
- Human Perception Filter that models the sense of touch in software to determine how a haptic effect will likely feel.
- Physical parameters:
 - Acceleration (on the surface)
 - Force / Trigger threshold (if we are talking about "functional safety")
 - Displacement (not visible, less than 300 μm)
 - Frequency: haptic (< 300 Hz) & sound (designed, not unwanted)
 - Response time (latency)

In order to specify and optimize all these parameters already during development, one or more test systems must be used. In addition, all these data are necessary for the description of haptic feedback (e.g., acceleration values under the influence of force, latency, and trigger thresholds must be measured).

9 Representative case studies

The below case studies are based on responses collected with this web form [\[Case Study Form\]](#). You may use that form to submit your own case study for consideration to be included in a future version of this document.

9.1 Haptic touchscreen demonstrator



Source: Immersion

Submitter: Immersion Corporation
Users: Automotive OEMs, tier 1 suppliers
Haptic champion: Tier 2 suppliers
BOM: USD\$20–30

Overview

Edison is a Haptic Design Touchscreen that enables automotive makers to experiment, test, and define haptic experiences in the early stages of the automotive HMI development in the prototyping and design stages before the system design stage. It enables the users to try incorporating haptic effects on their built in HMI and tweak effects to deliver a good user experience.

Customer goals

Safety (Reduce driver distraction); User Experience; Industrial Design Objectives; Prototyping tool

Addressed KPIs

Provide customers with a prototype to create own HMI with haptics, broader haptic adoption in the automotive market.

Scope of the project

Demonstrator; Haptic design touchscreen

Success

As of publication, the project is underway and about to be completed. It's currently being evaluated and will take a few months before the success criteria can be listed.

Technology used

Vibrotactile feedback - Mechanical vibration. Hardware components used are all Automotive rated including Piezo actuator, Microcontroller and Amplifier/Driver.

Challenges encountered

The mechanical vibration isolation and the screen selection. While the screen was meeting the automotive temperature range, the overall design of the screen posed a few mechanical challenges to isolate the noise issues since some of the parts of our display were getting excited at resonant frequency thereby resulting in additional noise/vibration.

Key learnings

1. Screen selection, analysis and design is very important. Important to talk to the screen manufacturer to identify a good solution for haptics. Screen design needs to have a natural frequency much higher than the maximum haptics design frequency range.
2. Identification of characteristics of the screen with Finite Element Analysis will help design a good mechanical suspension to ensure there is complete isolation of vibration when the actuator is excited. Optically bonded screens would potentially be a better solution only if all parts in the system are designed to not resonate in the haptic frequency range of interest.
3. Designing the HMI early on and planning the type of effects to be deployed and the kind of user experience that needs to be delivered is good to have in the initial stages.
4. The mounting of the haptics system ground support (mass and isolators) significantly impacts the overall performance and should be clearly defined with the customer.

9.2 Production luxury haptic touchpad



Source: Innovobot

Submitter: Innovobot

Users: Automotive OEMs, tier 1 suppliers

Haptic champion: OEM

BOM: Not specified, though it is notable that the BOM of this touchpad was lower than the haptic paddle joystick that was previously used in this vehicle.

Use case overview

Touchpad implemented in the luxury brand Lexus. Now widely available in most models it has replaced a second generation, kinesthetic joystick. The latest version tested the haptics are applied for motion events only, a parallel mechanical mechanism is included to provide a mechanical click response to select actions. Despite this added complexity the device is still much less complex than the part it replaces. Testing indicates that the haptic responses are generated by an ERM, with a fairly well designed actuator and effect design providing a click like experience rather than a typical ERM, pager like experience that can be found with ERM solutions.

Customer goals

User Experience, Industrial Design Objectives

Addressed KPIs

Replacement of high cost joystick with lower cost touchpad.

Scope of the project

Multiple models equipped

Success

The project was successful as it is now the standard across the brand, it was also a success for the tier supplier as they replaced the previous supplier.

Technology used

The touchpad uses vibrotactile haptics generated by an ERM, haptics are used for user input other than select, which is done with mechanical buttons.

Key Challenges

Space and cost.

Learning takeaways

When designers do not know what is possible with haptics, costs are increased. With better design select confirmation could have been provided by haptics reducing costs.

Additional resources

https://drivers.lexus.com/lexusdrivers/videos/video-details?id=templatedata/ResourcesMain/ResourceVideos/data/technology/technology_Remote_Touch_Interface_Touchpad.dcr

9.3 Audi touchscreen



Source: Innovobot

Submitter: Innovobot

Users: Automotive OEMs, tier 1 suppliers

Haptic champion: OEM

BOM: Estimated less than USD\$25 impact to bill of materials for HMI

Use Case Overview

Dual touch screens implemented in the Audi A8 luxury vehicle. The upper screen is an infotainment display allowing GPS navigation and other CID features, the lower panel is used as a button panel for HVAC controls. Based on testing it appears that each unit is using a solenoid based approach providing about 1G (peak to peak) acceleration on each of the displays. The feeling is somewhat inconsistent with the feeling and strength of the Audi touchpads found in the Q7. It is of note that this display does not seem to have proliferated across the Audi line. Of note the design appears to be applied by a display provider previously considered a tier 2 supplier and not a traditional tier 1 supplier.

Customer Goal

Mechanical feel on touchscreens, User Experience, Industrial Design Objectives

Addressed KPIs

Mechanical feel on touchscreens

Scope of the project

Multiple models equipped

Success

Production on one model. Strength was lower than expected.

Technology used

The solution is solenoid based

Key Challenges

Implementation of pressure and haptics required a custom-built solution. Specification was pushed by OEM to tier.

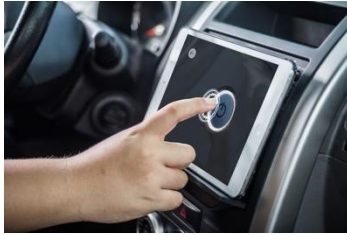
Learning takeaways

If the OEM specifies the feature, haptics will be implemented.

Additional Resources

<https://www.audi-mediacycenter.com/en/the-new-audi-a8-the-future-of-the-luxury-class-9312/controls-and-infotainment-9314>

9.4 Surface friction display



Source: hap2U

Submitter: hap2U

Users: Automotive OEMs, tier 1 suppliers

Haptic champion: OEM

BOM: Between USD\$10 and \$20

Use Case Overview

Enhance driver interaction with touchscreen interface, using ultrasonic lubrication.

Push feedback replaces visual feedback to acknowledge user action.

Haptic texturing provides mechanical feedback on various widgets (slider, wheel, etc ...), allowing for precise parameters tuning (temperature, sound level, ...).

Combined with gesture recognition, haptic controls can be provided anywhere on top of the display. The user action is determined by its gesture rather than the finger position, while haptic feedback provides validation. Those three solutions combined together enable an eyefree interaction for the driver.

Customer Goal

Safety (Reduce driver distraction), User Experience

Addressed KPIs

Mechanical feel on touchscreens

Mental load / driver distraction (time eyes off road)

Scope of the project

Demonstrator

Success

Yes, demo was approved by the final customer. Positive user satisfaction surveys.

Technology used

Ultrasonic lubrication. The friction modulation generates push and release feedback when the user interacts with the controls, or is triggered versus the user finger position. BOM includes piezo actuators & drivers.

Software includes firmware embedded inside the microcontroller, API & dedicated SDK to design the UX/UI.

Key Challenges

Noiseless solution, large display size. Define easy to get gesture controls versus user experience and HMI features

Learning takeaways

If the OEM specifies the feature, haptics will be implemented.

Gesture recognition allows for better eyeless interaction. After a first discovery step, the user gets familiar with the dynamic controls position and can have precise controls of various settings (volume, temperature).

Modifying the user interface according to new haptic features produce great results.

9.5 Mid-Air Haptic Gesture HMI



Source: Ultraleap

Submitter: Ultraleap
Users: Automotive OEMs, tier 1 suppliers
Haptic champion: OEM
BOM: USD\$75 - \$250

Use Case Overview

DS Automobiles wanted to focus on limiting visual pollution and reduce the contemporary onus on touchscreens by enabling gesture interaction for infotainment features and augmenting with mid-air haptic feedback to enhance the sense of agency in mid-air interaction. A bespoke solution was developed involving a split arrangement of mid-air haptics arrays to meet the form of the interior as well as acoustically permeable mesh to deliver seamless style integration.

Customer Goal

Reduced visual distraction, craftsmanship and luxury, easy integration into HMI toolchains, de-cluttered interior.

Addressed KPIs

Salient mid-air haptic sensations, bespoke hardware packaging, haptics tangible through aesthetic covering.

Scope of the project

Integrate into a concept vehicle (DS Aero Sport Lounge)

Success

Concept car was exhibited on the world stage at the Geneva motor show and critically acclaimed in consumer reports.

Technology used

Mid-air gestures are captured through a binocular infrared camera and interpreted by hand-tracking algorithms. This information is relayed to a phased array of ultrasonic transducers that emit ultrasound.

Key Challenges

Centre Console packaging space required a custom layout of transducers in order to retain aesthetic styling.

Learning takeaways

Bespoke solutions are time consuming for initial prototyping and design evaluation.

Additional Resources

<https://www.ultraleap.com/company/news/case-study/ds-automobiles-gesture-control/>

10 Resources

10.1 Vendors

Company name	Type	Solution / Product
Immersion Corporation*	Technology provider	Haptic Technology Solutions, Product Development Kits, Haptics Innovation Program
TDK*	Component supplier	PowerHap & PiezoHapt piezo actuators, evaluation kits, design guides
Interhaptics*	Haptics Software provider	Haptics design suite to customize the haptics experience.
Hap2U*	Technology provider	Haptic Technology Solutions (Ultrasonic Lubrication), Product Development Kits, Haptics Innovation Program, Software UX Design Tools
Boréas Technologies*	Electronics component supplier	Piezo Haptic Drivers (Integrated Circuits)
Nanoport Technology*	Motor supplier, Technology provider	TacHammer Wideband motors, VectorHaptics firmware, APIs, and Developer Kits.
Ultraleap*	Technology Provider	Mid-air haptics modules and development kits, hand-tracking software licensing, Binocular Infra-Red Camera Hardware, design tooling.
GREWUS*	Component supplier Characterization systems & services	electromagnetic & piezo actuators, Haptic Solution Provider, haptic test-system and evaluation board
Innovotive	Solutions provider	Haptics system design, tools, training and know-how from prototype to production.

*HIF Member

10.2 Further information

<https://hapticsif.org/>