HaptiMoto: Turn-by-Turn Haptic Route Guidance Interface for Motorcyclists

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ABSTRACT
A national study by the Australian Transport Safety Bureau revealed that motorcyclist deaths were nearly thirty times more prevalent than that of drivers of other vehicles. These fatalities represent approximately 5% of all highway deaths each year, yet motorcycles account for only 2% of all registered vehicles in the United States. Motorcyclists are highly exposed on the road, so maintaining situational awareness at all times is crucial. Route guidance systems enable users to efficiently navigate between locations using dynamic visual maps and audio directions, and have been well tested with motorists, but remain unsafe for use by motorcyclists. Audio/visual routing systems decrease motorcyclists' situational awareness and vehicle control, and thus elevate chances of an accident. To enable motorcyclists to take advantage of route guidance while maintaining situational awareness, we created HaptiMoto, a wearable haptic route guidance system. HaptiMoto uses tactile signals to encode the distance and direction of approaching turns, thus avoiding interference with audio/visual awareness. Our evaluations demonstrate that HaptiMoto is both intuitive and a safer alternative for motorcyclists compared to existing solutions.

Author Keywords
Tactile interface; vibro-tactile; advanced traveler information system; route guidance.

ACM Classification Keywords
H.5.2.g. Information Interfaces and Representation (HCI): Haptic I/O.

INTRODUCTION
Navigational support tools are valuable resources for motorists and motorcyclists alike, and paper maps have been the norm for many years until the introduction of modern technological solutions such as commercial GPS systems, virtual displays, and turn-by-turn audio and visual navigation devices. With Advanced Traveler Information Systems (ATIS), vehicle drivers have access to information for planning routes, viewing traffic conditions, looking up restaurants, and so on [10]. The most common utility of ATIS is in-vehicle route guidance and navigation system (IRANS) [7], which serves dual purposes of route planning and guidance. The route planning feature is used to plan a driving route between two known locations, while the route guidance feature is used to provide turn-by-turn guidance to drivers in motion. A combined dynamic visual and audio interface is most common for providing in-transit route guidance information to drivers. One notable example is Google Maps, a popular route guidance application for drivers, which uses a visual interface for providing the driver's current location on a map, the upcoming turn, and the distance to that turn. Google Maps also uses an audio interface to alert drivers of the approaching turning direction and distance.

However, these audio/visual interfaces are not suitable for motorcyclists, since they require their visual and auditory channels to maintain awareness of the environment around them. Such interfaces could obstruct the motorcyclist's view, decrease their acoustic awareness, and magnify their inattention while traveling, which in turn raises the probability of being involved in an accident [7, 9]. Audio interfaces have also been proven in military field tests to throw off team commanders' sense of direction from other audio inputs; commanders donning wearable audio devices (e.g., earbuds) only realize gunfire being directed at them after observing other team members with unimpeded listening ducking for cover. The human ear is very good at focusing in on certain sounds while blocking out others. While not a concern for motorists whom are accustomed to blocking out outdoor noises while driving, this can be detrimental to motorcyclists in those cases where outdoor sounds are crucial to their situational awareness.

In addition, a national study by the Australian Transport Safety Bureau revealed that motorcyclist deaths were nearly thirty times more prevalent than that of drivers of other vehicles [1]. Motorcyclist fatalities represent approximately 5% of all highway deaths each year, yet motorcycles account for only 2% of all registered vehicles in the United States [2]. The U.S. Center for Disease Control and Prevention report on motorcycle accidents further reveals that over 34,000 motorcyclists were killed and an estimated 1,222,000 persons were treated in the emergency room in the United States for nonfatal motorcycle-related injuries from 2001 to 2008 [5].

CHI 2014, April 26–May 1, 2014, Toronto, Ontario, Canada.

ACM 978-1-4503-2473-1/14/04..$15.00.
http://dx.doi.org/10.1145/2556288.2557404

Alternatively, current smartphone navigation systems encourage touch interaction; a simple swipe might be needed to clear an incoming text message or phone call, or even awaken the screen to view the map for approaching turns. On the other hand, any touch interaction is hazardous for motorcyclists, whom must keep one hand on the brake and the other on the gas at all times. Requiring touch interaction for motorcyclist navigation would be akin to a car interface requiring drivers to use their right foot while driving and, furthermore, requiring that the driver take off their shoe before interacting with that interface, since common motorcycle gloves will not work with a smartphone. Thus, there is a need to create an interface for a hands-free in-transit route guidance system that also does not reduce motorcyclists' situational awareness.

Haptic interfaces supply information through touch feedback, and can be used in situations where the visual and audio medium is overloaded with information. According to multiple resource theory [64], visual, audio, and tactile channels can be used by individuals to acquire information without drastic increases in brain processing resources for most situations. With motorcyclists, visual and audio channels are already overtaxed due to the noise from the motorcycle itself, elevating the danger of causing an accident. The use of a tactile modality for providing directional cues is further supported by van Erp's framework for choosing an information modality [62] and by experiments conducted by Cao, *et al.* [11].

Our hypothesis is that a tactile modality is effective for communicating turn-by-turn information to motorcyclists. Therefore, we propose HaptiMoto, a haptic interface system for in-transit route guidance that provides turn-by-turn information to motorcyclists during travel. The scope of our contributions do not include route planning, which are obtained through Google Maps on a smartphone kept in the motorcyclist's pocket, but focus instead on the valuable activity of communicating directions while motorcycling. The contributions of our work include:

1. Enumerating the differences in haptic interface design requirements between pedestrian and motorcyclist route guidance.
2. Locating optimal placement of tactors on a haptic vest for motorcycle route guidance.
3. Designing a set of tactile signals to encode direction and distance for approaching turns.
4. Identifying travel scenarios capable of evaluating a route guidance system for motorcyclists.
5. Demonstrating the effectiveness of a tactile medium to communicate turn-by-turn directions to motorcyclists, including the ability of users to perceive and understand tactile signals, react appropriately to directional cues, and perform appropriate turns with HaptiMoto.

RELATED WORK

While there is extensive research in tactile navigation interfaces for pedestrian and car navigation [7, 10], research in analogous tactile route guidance interfaces for motorcyclists is limited. Thus, our work is significantly influenced by existing work in interfaces for other forms of navigation, as well as by psychophysical experiments on tactile sensitivity, multiple task management, and change blindness to haptic cues [21, 59, 64].

Human Factors Research in Tactile Interfaces

Research on orienting users with tactile interfaces includes conveying driving directions [14, 26, 59, 63], bicycle navigation [44, 56], and pedestrian navigation [13, 43]. Van Erp examined the navigation of pilots, motorists, and soldiers, and devised a theoretical framework to decide the appropriateness of a communication modality based on the primary and secondary task [62]. For a motorist, driving is a task secondary to navigation, while the reverse is true for motorcyclists. Van Erp [62] suggests the use of a tactile modality in such circumstances, including dual-task environments (e.g., navigation and driving). There is less workload for cueing tasks when haptic cues are used in combination with audio or visual cues, rather than with audio or visual cues alone [16, 63]. Additionally, research comparing tactile and auditory modalities to convey driving directions in cars shows tactile input works better than auditory [11], further motivating the use of haptics for motorcycle navigation.

Poppinga, *et al.* [44] designed Tacticycle, an interface using a combination of the visual and tactile medium to navigate bicyclists. Tacticycle uses "drift to destination" to guide bicyclists by providing the destination's direction relative to their orientation like a compass, but was not designed to either efficiently navigate between two locations or alert them of approaching turns. Tacticycle's typical use cases were also limited to short routes and slow navigation. Steltenpohl and Bouwer [56] designed a vibrotactile belt called Vibrobelt to provide turn-by-turn navigation signals for bicyclists, where signals are provided at 50 m and 10 m before upcoming turns. We contend that bicyclists are instead similar to pedestrians; bicyclists' have ample time to respond to navigational cues due to much slower travel speeds and can more easily pull over to the side of the road to confirm navigational aspects. Vehicle speed also determines when a bicyclist needs to be warned of upcoming turns; low speeds and small variations in bicyclist speeds allow designers to signal riders at predefined distances before a turn (e.g., Vibrobelt), while motorcyclists can travel anywhere between 10-75 mph. Motorcyclists cannot afford to be distracted by navigational cues due to a higher average and wider range of speeds, especially since they share the travel speed hazards of motorists and the exposed vulnerabilities of bicyclists and pedestrians. The vibrotactors' positions in Tacticycle's handlebars and Vibrobelt's belt are also not appropriate stimulus locations for motorcyclists, since these will increase change blindness [23].

Tactile direction cueing for motorists has been shown to be effective and tested in several configurations, including on a three-by-three array of tactors on a chair [59], an eight-by-eight array of tactors on seats [14, 63], and left and right haptic sensations on a steering wheel [16]. An *on-thigh* vibro-tactile belt containing eight tactors around the thigh successfully alerts pilots of plane orientation, with two tactors specifying the line representing the direction of gravity [51, 52]. Researchers have found haptic driving modalities safer than electro-tactile or force-feedback systems while driving cars [12]. When compared to a visual navigation display, the tactile navigation display did not increase motorists' mental workload. We believe motorists have smaller workloads than motorcyclists, and our motivation focuses on building a usable vibro-tactile guidance system that does not increase motorcyclists' workload.

Tactile Interfaces for Pedestrian Navigation

Pedestrian navigation systems are designed to accommodate various pedestrian types, such as tourists in unfamiliar environments [43, 58], soldiers in sensitive environments [13, 17, 18], and vision-impaired individuals in bustling environments [27, 39], whom use tactile alerts, smartphone vibration alerts, or wearable devices such as vibrotactile belts and vests. The literature provides ideas about affordances and analogies that could be used for designing vibro-tactile signals to provide directions. The *magic wand* interaction metaphor points the device at a distant object to learn more about its presence, and accesses its corresponding information [20]. Users must often scan their surrounding by either turning their bodies or physically waving the mobile device with their arms stretched out forward, or turning their bodies around with the mobile device in their possession [35, 36]. This has been used for different purposes, such as improved guidance for the visually-impaired [34], flexible routes for wandering tourists [48], and streamlined meetups for social groups [65]. Although the *magic wand* metaphor has proven to be effective and intuivite [35, 48, 65], it requires user motion that is not feasible for motorcyclists whom must keep their body and hands in a fixed location. The *sixth sense* metaphor is often used with wearable devices such as multiple vibrating tactors, enabling users to derive the location or navigation of their target destinations in relation to their current location and orientation [13, 31, 41, 42, 43, 46, 50, 58]. *Sixth sense* interfaces benefit users through more passive interaction (i.e., no additional user motion), but has a steeper learning curve for understanding the directional meaning of the feedback.

Sixth Sense haptic systems include tactile belts and vests. In general, haptic belts [19, 40, 54] outperform early haptic vests that generated straight-lined patterns [28, 49], as tactile belts allow for 360 degrees of location feedback. Recent vest improvements support relative point vibrations on the back of the user (e.g., left, forward, right) during navigation [13, 17, 18], allowing for more sophisticated navigation. We have experimented with both belts and vests in our work with motorcycles, and discovered that the hips and waist receive a significant amount of vibrational noise from the motorcycle. This made a tactile belt impractical for our use, and we instead chose a tactile vest that affords the "tap on the shoulder" analogy [45].

Psychophysical Research

Auditory directional signals perform better than visual directional signals for motorcyclists, as they reduce visual overload [15, 32, 57] while still presenting high priority and intermittent information [10]. For motorcyclists, the use of the auditory channel comes with certain limitations and increased risk as it reduces acoustic awareness. Motorcyclists need to have acoustic awareness in order to respond to unexpected events [9]. Moreover, external noises such as engine or wind turbulence noise could make directional signals inaudible. At 70 mph, the wind turbulence is approximately 100 dB and is a major source of noise at high speeds [9]. The Psychological Refractory Period (PRP) states that when two tasks require simultaneous response, users decide on performing one task and queue the response for the secondary task. The delay in performing the queuing task is called the PRP period, which reduces the attention in detecting critical events caused by the PRP effect [25]. The PRP effect further motivated us to not overload motorcyclists' visual or auditory channels.

The effectiveness of the tactile medium depends on the perception of the tactile stimulus, which is dependent on the stimulus strength, count, location, environmental change blindness, and user sensitivity [22]. Users can distinguish up to twelve different angles of directional information, with errors in judgment within 10° to 17° [61]. The HaptiMoto vest provides tactile signals on the rear shoulders and lower-center back, as shown to be effective by prior experiments [45].

Change blindness is induced when multiple stimuli are presented simultaneously on similar medium, which can reduce communication effectiveness. Driving involves both visual and auditory input mediums of the user, so change blindness is higher when the user is provided audio/visual directional cues. Change blindness is higher for tactile stimulus when it is applied to moving parts of the body or close proximity to other tactile stimulus [23, 53]. For example, motorcyclists use their arms to steer, while their arms and legs are close to the vibrational noise of the motorcycle. Thus, it is ineffective to provide tactile direction stimulus to either the arms or the legs of motorcyclists. The tactors in the HaptiMoto vest are located on the upper part of the body, and also away from moving parts of the body or those close to motorcycle vibration (e.g., hips, waist). Errors caused from change blindness can be further reduced by repeating the tactile signals [22].

Navigation research supports the use of turn-by-turn route guidance for navigating users; turn-by-turn signals can be associated to view-action pairs, where a driver gets a directional signal for a turn and performs the corresponding turning action [60, 15]. According to Dingus [15], directional information is sufficient for route guidance and any other information is potentially disruptive. Information about a turn signal should contain three important parts to it: which direction to turn, at what specified distance, and onto which specific road.

The timing of the tactile signals and the amount of time between them are as important as the directional information, where timing should take into account the user's reaction time, decision-making time, and maneuvering time. The reaction time for drivers is between 0.75 seconds and 1.50 seconds, with 2.50 seconds being the preferred reaction time for roadway navigation design [33, 37]. Navigation timing can also depend on a fixed distance approach [55] or a lead distance approach [10]. In one fixed distance approach [55], the first message was given 365 meters before a turn on parkways, 213 meters on a four-lane road, and 122 meters on a two-lane road, while the second message was given 61 meters before the turn. The lead distance approach also depends on the speed of the vehicle [10]. It is defined as the distance before a user needs to be warned of an approaching turn for them to make the turn comfortably, and suggests an equation for the minimum, ideal, and maximum lead distance required for a user to make any turn. The lead distance and timing of the directional signal can be calculated from the vehicle's speed.

Given a driving task for a certain distance and a travel route, several standard measures exist to determine the effectiveness and attentional demands of the task at hand, including the NASA TLX Subjective Workload Test [24, 38, 55]; reaction time required to respond to directional cues [55]; Subjective Workload Assessment Test (SWAT) [32, 47]; number of correct, incorrect, missed, and near-miss turns [32]; mean velocity, absolute deviation in velocity, and variance in acceleration, where higher variation means navigational cues take more attention disrupting the speed of the vehicle [32]; and total driving time to complete a route [38]. In our evaluation, we measure the motorcyclist's completion time and also their number of correct, incorrect, and missed turns.

DESIGN AND IMPLEMENTATION

Our system consists of a tactile vest with adjustable straps to fit different users and an accompanying mobile Android app. The vest is equipped with a LilyPad Arduino [3], a BlueSMiRF Bluetooth module [4], and also three LilyPad Vibe Boards (i.e., vibrational tactors) [6] located at the lower back and rear left and right shoulders (Figure 1(a)). The mobile app provides GPS location updates, the user's alignment, and a processing unit for calculating directional cues. The directional cues are communicated to the Arduino via Bluetooth, where the Arduino serves as the microcontroller for the navigation system by activating the vibrational tactors indicating the directional cues. We selected these components specifically for their lightweight characteristics and seamless integration into the vest's fabric with conductive threads (Figure 1(c)), since integrating the vibe boards with clothing improves how users perceive tactile stimulus [29].

The design choice for presenting directional cues involves sending tactile signals to the user's rear shoulders (Figure 1(b)), since users found the locations both intuitive and effective in communicating navigational information without prior directional training for the domain of walking [45]. That is, users naturally turned in the same direction as the received signal without prior instruction, which they described as akin to "a tap on the shoulder". We were further motivated by this design choice for motorcycling compared to other locations, since it was less prone to interference from vehicle vibration and air turbulence [23, 53]. Moreover, the co-location of haptic cues and target direction (i.e., left and right tactors mapping to the left and right direction, respectively) reduces the number of turning errors committed by the user [26]. We also selected the length of our tactile signals' pulse lengths as 300 ms for navigational cues, since users perceived pulses on their rear shoulder less than 500 ms in duration as analogous to being pulled or tapped toward that side (e.g., pulling the left shoulder back to turn left) and greater than 700 ms in duration as analogous to being pushed toward the other side (e.g., pushing the left shoulder forward to turn right) [45]. The number of these pulses encodes the relative distance to an upcoming turn, and the duration between pulses and the number of these pulses are dimensions that serve to encode the sense of urgency or nearness to that turn [62, 63].

From our evaluations, we discovered several key differences between pedestrian and motorcycle navigation. First, people require less awareness of their surroundings while walking compared to motorcycling due to its slower speed. That is, the perception and timing of directional signals presented is crucial for motorcyclists. Second, the lead distance to convey direction for motorcycling is larger than for walking due to motorcycle's higher travel speeds. Third, pedestrians can change orientation at any direction with walking, while motorcyclists are restricted by the road's orientation during travel. Therefore, we do not rely on the motorcyclists' orientation to calculate the directional cue for the next turn.

(a) The vest. (b) The tactors. (c) The schematic.

Figure 1: The HaptiMoto vest with Lilypad Arduino (A), battery (B), BlueSMiRF (BT), and Vibe Boards (L,R,S).

The timings of the directional cues were specifically adapted for motorcycle route guidance as four primary directional signals: left, right, straight, and U-turn. The tactile signal dictionary is shown in Figure 2. Directional haptic cues are provided either every three seconds or fifteen meters traveled except for U-turns, which are provided continuously.

Figure 2: The dictionary of HaptiMoto's tactile signals.

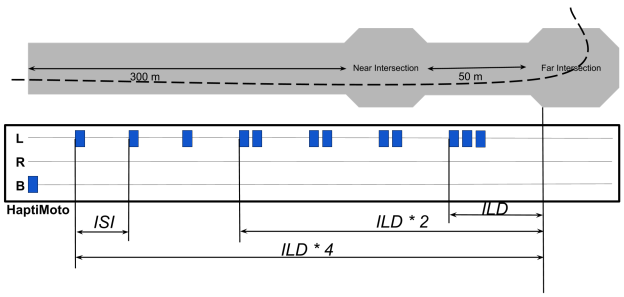


Figure 3: An example of the tactile signals presented to users before an approaching left turn, where *ILD* is *Ideal Lead Distance (x)* and *ISI* is *Interstimulus Interval* (i.e., either 3 seconds or the time taken to travel 15 meters).

We encode the direction of the approaching turn by the location of the vibro-tactile stimulus, and the distance to the approaching turn by the number of pulses. Tactile signals for turns are provided at $4x$, $2x$ and x distance intervals before the turn, where x is the ideal lead distance proposed by design guidelines from the United States' Department of Transportation [10]. Users receive a straight signal when they are beyond $4x$ distance from the location of the approaching turn, a single shoulder pulse every three seconds between $4x$ and $2x$ distance, two shoulder pulses every three seconds between $2x$ and x distance, and three shoulder pulses every three seconds within x distance:

1. *Minimum lead distance* = (speed * 1.637) + 14.799
2. *Ideal lead distance (x)* = (speed * 1.1973) + 21.307
3. *Maximum lead distance* = (speed * 2.22) + 37.144

Figure 3 illustrates the timings of the tactile signals during motorcycle travel. Single pulses for tactile signals activate for 300 ms, while multiple pulses activate for 150 ms.

EVALUATION

The central aim of our evaluation is on the feasibility of haptic motorcycle navigation, which we evaluated in two parts: the usability of HaptiMoto's tactile signals with no training and users' motorcycling abilities with HaptiMoto guidance for three scenarios. As such, we evaluated our design using a study population on four distinct circuits, with the purpose of testing the following hypotheses:

1. The users perceive and understand the tactile directional cues (*h1*).
2. The users react appropriately to tactile directional cues (*h2*).
3. The users understand a tactile directional cue well enough before approaching a turn and comfortably makes that turn (*h3*).

Before motorcycling, we introduced users to HaptiMoto by having them wear the vest and ensuring the tactors fit snuggly against their shoulders and center of their back. We then required users to wear a safety helmet, gloves, shoes, and jacket. Each tactile signal was presented to them to ensure that users perceived it, but they were provided no explanation on the meaning of any signal given to them. All of our users are also experienced motorcyclists.

Evaluation I

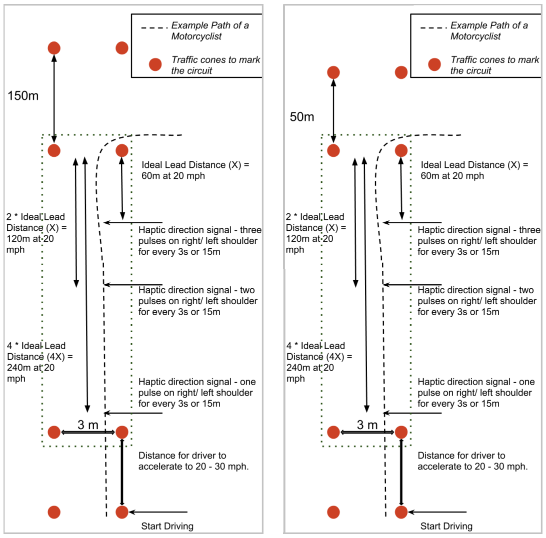
In order to evaluate the users' ability to perceive and understand (i.e., *h1*) and react to (i.e., *h2*) haptic cues for direction, users motorcycled into an open parking lot while wearing the vest and reacted to the vest's tactile commands as they interpreted them. Starting at a pre-specified starting point, we asked users to accelerate to a speed of between 20 to 30 mph before reaching a second point in the circuit marked by red traffic cones. We anticipated users responding to the provided directional instruction, which was a single pulse chosen randomly that specified one of four possible directions of either straight, left, right, or back, as soon as they reached the specified speed. Each direction was tested four times in a random sequence for a total of twelve directions. The experimenter noted the number of correct and incorrect turns made during each task, and we used the overall turn accuracy as the metric to evaluate hypotheses *h1* and *h2*.

Evaluation II

The second evaluation tested the ability of users to perceive haptic cues, react to them, and make turns comfortably (*h1, h2, and h3*) through four different circuits, all presented randomly to the user, and included double turns, single turns, straightaways, turns after 50 meters, and turns after 150 meters. The circuits were chosen to reflect common driving scenarios faced by motorcyclists while in motion. The distance of 150 meters between intersections was chosen from road and highway guidelines [8, 37]. According to road geometric design guidelines, the minimum distance between intersections should be 150 meters for roads with 20 mph speed limit. 50 meters is the recommended minimum distance between intersections for roads with 10-20 mph speed limits [8, 37]. The number of turns made in the correct direction, made at the correct intersection, nearly missed, and missed were recorded.

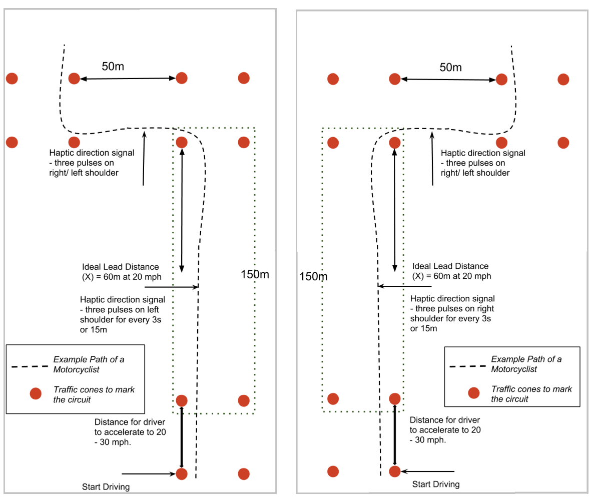
Figure 4(a) shows Circuit I with two intersections separated by 150 meters, where users would travel 150 meters before reaching the first intersection. The user would then have to decide on which direction to turn and the intersection on which they have to turn into, where the order and turn sequence was given at random. Figure 4(b) shows Circuit II with two intersections separated by 50 meters. The first two circuits helped us evaluate the users' ability to follow the navigation signals and perform turns correctly while traveling on a straightaway. Figure 3 shows an example scenario of tactile signals instructing users to turn.

Circuits III and IV reflect scenarios where turns are made in quick succession from one street to the next (Figures 4(c) and 4(d)). Users motorcycled on a 150 meter-long straight path to the first intersection in the circuits, where they sometimes attained significant speeds, and were instructed to turn either left or right by the tactile signal, before driving an additional 50 meters straight for another left or right turn. This scenario tested the users' ability to make turns in quick succession with HaptiMoto guidance.



(a) Intersection separated by 150 m (Circuit I).

(b) Intersection separated by 50 m (Circuit II).



(c) Circuit with two turns in quick succession (Circuit III).

(d) Circuit with two turns in quick succession (Circuit IV).

Figure 4: The circuits used in our user study.

We then asked users to motorcycle on the four circuits shown in Figure 4 at random with the HaptiMoto vest's directional cues. Users motorcycled on a parking lot with both real and distractor turn cones, and we asked them to accelerate to between 20 and 30 mph, where the ideal lead distance x is 60 meters at 20 mph and 110 meters at 30 mph. For this evaluation, users received one-, two-, and three-pulse notifications as elaborated in the description of HaptiMoto's implementation.

RESULTS

We recruited 16 participants in our user study, all male and between the ages of 25 and 30 years, inclusive. Each participant in the first part of the study performed a total of 48 turns for four directions (i.e., left, right, straight, back), where everyone performed the intended turn with 100% accuracy.

Figure 5 shows the results from Circuits I and II. For Circuit I, each participant performed tasks for each turn and intersection twice in random order. Together, the participants performed 52 correct left turns, 52 correct right turns, and 12 missed left and right turns from out of 128 turns performed. Six of the missed turns were due to being improperly fitted with the vest and thus not being able to detect the vest's tactile signals, at which point the vest was fitted on them again. Figure 5(a) shows the results from the data points where users could perceive the tactile signals, in which all users successfully chose the correct direction to turn. Seven users from the starting point of the circuit chose the nearer intersection to turn when HaptiMoto instead guided them to the farther intersection, while one user missed the nearer intersection and made the turn at the farther intersection.

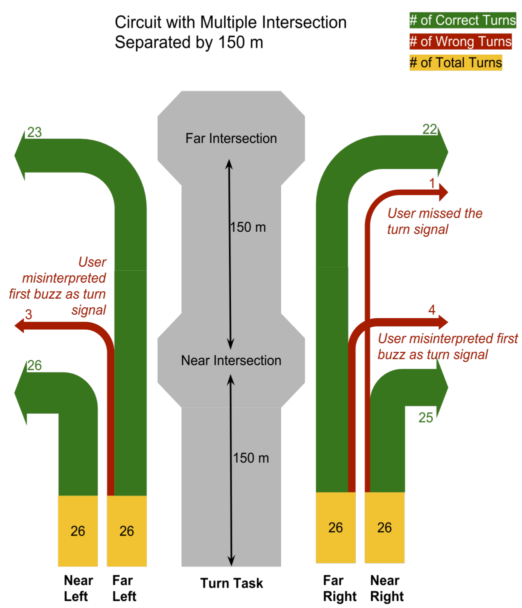
For Circuit II, participants performed each turning task once, for a total of 16 data points on each turn and intersection. Participants had to perform 32 turns each for left and right directions, and they all chose the correct direction to turn for each turning task. Figure 5(b) shows the number of correct turns and intersections made. Of a total of $32N \times N4 = 128$ turns, there were nine instances when a participant chose to turn at the nearer intersection when HaptiMoto instead guided the user to the farther intersection, and one instance where a participant turned at the farther intersection instead of the nearer one.

Figure 6 shows the performance of users for Circuits III and IV. Seven of those data points dropped stem from users' inability to perceive tactile signals, due to an improper vest fit. Each of the sixteen users had to perform 128 turns in total, choosing the correct direction in 100 instances while not being able to perceive the tactile signal in 28 instances. From a total of 50 instances in which a user makes a left turn at the first intersection, two instances involved the user missing the second turn at the appropriate intersection. In those two instances, users made the turn 25 m after the intended intersection. Figure 6(a) illustrates the number of correct and incorrect turns from users for Circuit III. Of the 50 total instances in which a user makes a right turn at the first intersection, seven of those instances involved the user missing the second turn at the appropriate intersection. In those seven instances, users made the turn 25 m after the intended intersection. Figure 6(b) illustrates the number of correct turns and the seven wrong instances for Circuit IV.

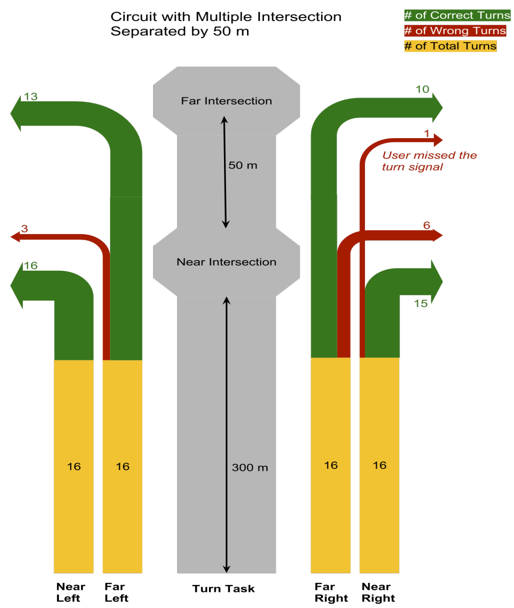
On a scale of 7, with 1 being the lowest usability rating and 7 being the highest, the mean rating for HaptiMoto's usability is 5.33 and its standard deviation is 1.11. The mean and standard deviation of the user ratings on the tactile signals for left, right, straight, and back are 6.12 ± 1.14, 6.2 ± 0.94, 6.2 ± 0.94, and 5.8 ± 1.68, respectively.

DISCUSSION

We can see from Evaluation I that users were able to perceive and understand the haptic cues (*h1*) and their intent (*h2*). While some users reported interpreting tactile signals for U-turns as straight or vice versa, this confusion did not seem to affect the accuracy for performing turns. In Evaluation I, users did not perceive the tactile signal for 40 of the instances,



(a) Circuit with intersection separated by 150 m.



(b) Circuit with intersection separated by 50 m.

Figure 5: Results from Evaluation II, with an illustration of the number of turning tasks performed and number of correct turns made in (a) Circuit I and (b) Circuit II from two intersections.

which we attribute to the looseness of the HaptiMoto vest. However, the results show that users did not have problems perceiving or understanding the haptic cues when the HaptiMoto vest was properly fitted.

Evaluation II shows that users could employ the haptic cues for choosing appropriate turns (*h3*), and also shows the errors while choosing a turn. The users chose correct turns with 91% accuracy in Circuit I, 84.4% in Circuit II, and 92.3% in Circuits III and IV. Seven of the eight errors were caused by users choosing to turn at the nearer intersection when they were instead guided to the farther intersection. These errors were due to users misinterpreting the tactile signals. The users reported that they made the turn after receiving two pulses for turning rather than three pulses, for which they were given no prior initial instruction. The three pulses were explained after the first mistake, and the users performed the turning task accurately in following turns. While there was some minor adapting to the system, we pleasantly discovered that users needed almost no instruction for the direction or distance feedback provided by the system, which emphasized the system's intuitiveness.

In the cases of Circuits I and II, one user missed making a turn for each circuit at a nearer intersection due to speeding too fast, and instead turned at the farther intersection. This user reported that he had reacted to the tactile signal too late to safely make the turn, so he continued on to the next intersection and turned there. This demonstrated that the tactile signals were strong enough to at least cause motorcyclists to be aware of correct turns that may be missed due to situations such as aggressive motorcycling. Although we did not consider this scenario when designing HaptiMoto, we

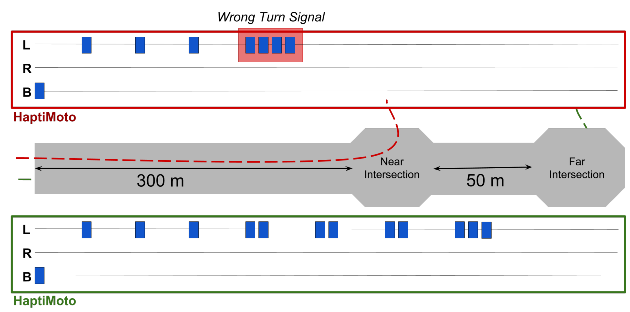


Figure 7: An example scenario where two sequentially GPS updates causes error in HaptiMoto navigation.

would like to keep the tactile signal's intensity at levels where motorcyclists may still be made safely aware of turns.

Additionally, there were nine instances from Circuit II in which users turned at the nearer intersection as HaptiMoto attempted to navigate them to the farther intersection. These errors occurred from a latency bug with the mobile app's built-in GPS feature, since HaptiMoto relies on the frequency and accuracy of the Android platform's GPS updates. These update can create instances where two GPS update events were received sequentially. While Android enables developers to set a minimum distance traveled or time elapsed between two location update events, there were some instances when these conditions were not met. As a result, this bug can cause two tactile signals to be grouped together as one. For instance, when a motorcyclist is 150 m away from the intended turn while traveling at 20 mph, HaptiMoto would send out a haptic signal to, say, the motorcyclist's left

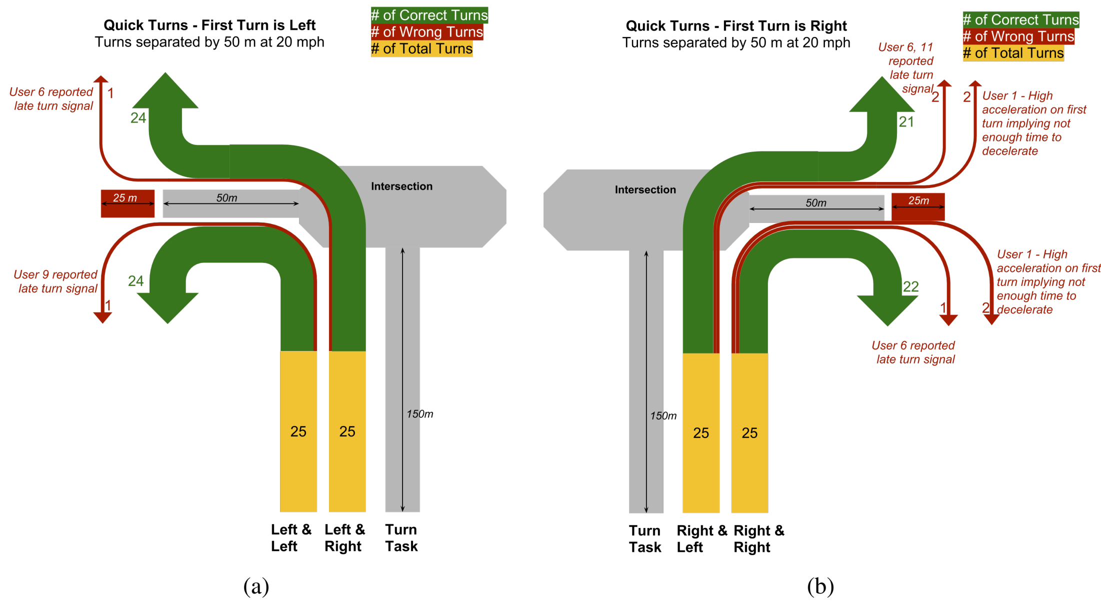


Figure 6: Results from Evaluation II, with an illustration of the number of turning tasks performed and number of correct turns made in (a) Circuit III and (b) Circuit IV from two turns in quick succession.

shoulder (Figure 7). The next tactile signal would then not be sent to the user until they have traveled an additional fifteen meters or three seconds. For the problematic case however, there were instances when such conditions were not met in-between GPS updates. The location updates were instead sent sequentially, resulting in two turn signals being sent simultaneously. We show this in Figure 7 on the right side of the route. The number of pulses in a signal determines the turn to be taken by the user, but when two turn signals are sent simultaneously, the users receive two separate two-pulse signals perceived as a single four-pulse signal. Since we observed users perceiving any signal which has more than three pulses as turning, they would therefore incorrectly make a turn immediately. We later addressed this bug by adding an additional time-elapsed check during the location update event.

We also observed that when users performed two turns in quick succession with HaptiMoto, there were nine instances from four users where they missed making the second turn (Figure 7). These users reported two different reasons for unsuccessfully making the second turn. Firstly, if they accelerate too quickly after making the first turn, it was difficult for them to decelerate in time to successfully make the second turn. Secondly, they reported instances when HaptiMoto's tactile signal for turning was received too late to safely make the turn. Our system is limited by the pace of Android's GPS updates, and therefore has some limitations in providing prompt tactile signals for turning. Since all four users were comfortably able to make a turn 25 m later after the second turn (i.e., 75 m later after the first turn), we can safely assume that HaptiMoto is able to support navigation of quick turns in succession when turns are separated by more than 75 meters. The errors indicate that motorcyclists require a minimum duration of time to make a turn [33, 37]. Otherwise, when the directional cues are presented within the ideal lead distance from the turn, they are more probable to miss making the turn [10].

Our results support haptic vests' viability as a motorcycle navigation interface, which employs the co-location of haptic cues and target direction [26, 49] and the encoding of warning lead distance with pulse count [10, 22]. Overall, we observed twelve user errors in the study due to weak contact between the user's body and tactors, as similarly noted in [28, 29, 61]. Turning direction accuracy also shows the discreteness and clearness of the haptic cues, with minimal interference from vehicle vibration noise [53]. Participants had suggested using a continuous vibrotactile signal instead of a three-pulse signal just prior to turning. However, our rationale for not implementing a continuous signal in this case is that it would distract the motorcyclist's attention away from the road and could also be perceived as annoying [30].

FUTURE WORK

One result from our user study revealed a flaw in the timing of HaptiMoto's tactile signals, which depended on Android's GPS update frequency that could affect users' navigation performance. We will work on a solution that will accommodate changes in GPS update frequencies. Another future work involves developing additional usability studies for HaptiMoto at higher speeds (e.g., 30-75 mph) above our current studies' range of 20-25 mph. We observed users' perception of the tactile signals decreased at faster speeds, and would like to expand HaptiMoto for alleviating issues from motorcyclists' increased workload in detecting navigational signals while traveling at faster speeds. Another future work we are working on is comparing HaptiGo with audio feedback, which has thus far shown haptic pulses to outperform audio feedback. Lastly, we would like to test HaptiMoto for navigation through complex junctions.

CONCLUSION

The primary purpose of this paper was to develop a wearable tactile navigational interface and demonstrate its effectiveness. Specifically, we tested three hypotheses: 1) haptic cues can be understood by motorcyclists, 2) motorcyclists can understand the haptic cues' intent, and 3) haptic cues can be used to perform routine motorcycle tasks. We designed an adjustable vest with vibrotactile sensors embedded on the the rear shoulders and center back, identified and implemented the minimum required information for route guidance (i.e., next turn direction, distance to approaching turn, and street to turn onto), and designed HaptiMoto's tactile signals to accommodate the information for route guidance. Lastly, we evaluated the system on three scenarios to test our three hypotheses. Our results show that HaptiMoto is an intuitive system that supports our hypotheses.

ACKNOWLEDGMENTS

We greatly thank Stephanie Valentine for her help in stitching circuits on the HaptiMoto vest, and the Texas Transportation Institute for their help in identifying no-traffic circuits in College Station, Texas for our user studies.

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