Design and Evaluation of a Steering Wheel-mount Speech Interface for Drivers' Mobile Use in Car

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Abstract— **Advanced mobile devices with speech recognition interface offered driver assistance in many ways. However, current interaction mode between drivers and the speech interface on mobile devices still generates obvious manual and visual distractions while driving. This paper proposed and prototyped a driver-friendly interface including a Bluetooth module mounted on the steering wheel and a HUD unit on the windshield. It allows drivers to remotely activate the speech interaction mode of mobile devices without taking their hands off the steering wheel, and read the visual display of mobile devices without looking away from the road. Evaluation of the new interface was conducted through a driving simulator experiment. Results showed that the interface designed in this study had reduced driver distraction and increased usability.**

I. Introduction

The revolution of mobile Internet and intelligent mobile devices, such as smart phone, has changed our daily life remarkably. By providing diversified functions and convenient location based services, mobile Internet drives people to use it anytime and anywhere. Meanwhile, another trend that drivers have spent significant amount of time on mobile Internet in their cars was also found, especially in developing countries [1]. Both trends have turned the car from a transportation tool into a multifunctional and mobile living space with Internet connection. Mobile devices could offer driver assistance services like navigation, location based search (LBS), and all kinds of applications (APPs) easily. However, the use of these new functionalities while driving will inevitably increase drivers' in-vehicle interactions and decrease their attention on driving, the primary task with the highest priority [2]. Driver distraction is one of the top threats to road safety. In-vehicle infotainment devices have become a major source of driver distraction in recent years [3]. Today, the popularity of mobile devices has led this distraction to be more and more severe. In order to mitigate driver distraction while using mobile devices for driver assistance, a safer and friendlier interaction design under the circumstance of driving is required.

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As an emerging interaction technology, speech recognition provides hands-free manipulation of in-vehicle devices while driving [2]. There is no doubt that speech recognition interface (e.g., Apple's Siri) is a suitable interaction approach; however, most related Apps on mobile devices failed to merge driving context into their consideration of interaction design. Normally, a speech recognition App aims to navigation or LBS requires the driver to press a push-to-talk (PTT) button to activate the listening mode, then presents searched results either by visual or audio output. Driver needs to keep holding the device until the searching task or input task finish. In this regard, speech recognition is just a new way of information input rather than a new way of interaction. To satisfy consumers' technological demand, many automobile manufacturers have recently developed in-vehicle infotainment systems (IVIS) with speech recognition or worked on integrating smart phone services into their IVIS. Nevertheless, automobiles cannot be updated easily as durable goods. On the contrary, mobile devices are changing rapidly with the development of powerful CPUs and cutting-edge operating system (OS). It provides a much easier access to speech recognition technology and other natural interfaces for the majority of drivers. Therefore, finding an easy way to optimize drivers' current in-vehicle use of mobile devices is meaningful and practical to road safety.

In this study, an expanded speech interface based on the original speech recognition feature of regular smart phones was designed for in-vehicle mobile device use. We mainly focused on redesigning the input and output (I/O) mechanism of smart phone to fit drivers' dynamic behavioral mode while driving. A remote Bluetooth control was applied as the input media to activate the speech recognition interface of the mobile device. A head-up display (HUD) was adopted as the output media to show visual presentations of the mobile device. By comparing with the traditional "hand-held" mode of smart phones, the safety, efficiency and usability of the new interface were examined through a driving simulator study.

II. Related Works

Modern information technology and mobile devices provides drivers an opportunity to use travel time for diversified works and entertainments [4]. Those functionalities like LBS and navigation are very helpful for driving. However, these in-vehicle secondary tasks have raised safety concerns at the same time [5, 6, 7].

A. *Mobile Internet in Driving Context*

Recent studies have shown that mobile internet had run into cars aggressively either by drivers' personal use of smart devices [8] or automotive manufactures' integration of mobile internet and IVIS, e.g., BMW's iDrive [9] and Roewe's iVoka [10], the latter one was developed on Andriod platform. The advantages of car-integrated IVIS include its specific design for in-car use and respect to laws and regulations about driving safety. However, their disadvantages were identified as much shorter product life cycle compared to cars, inflexibility of human machine interaction, increased manufacturing cost, etc [11]. Therefore, researchers in both academia and industry started trying to integrate existing smart mobile devices into IVIS [11, 12]. Besides, mobile device makers also targeted to develop in-vehicle oriented applications, such as Apple's Carplay and Google's Google Projected Mode, which allowed drivers to duplicate their mobile phone display to the IVIS display with a driver-friendly layout [13, 14]. However, all the systems above only fit limited car models and still require driver's hands-off-wheel operation, at least when activate the speech recognition interface.

B. *Driver Distraction Caused by Mobile Devices*

Calling and texting via mobile phone while driving have been proved to increase the possibility of road crash [15]. According to the report from Governors Highway Safety Association, 25% of car crashes in the United States were related to drivers' use of mobile phone while driving [16]. Driver distraction caused by mobile use can be categorized to visual, cognitive or manual in usual, reflecting driver behaviors of looking away from road, approaching mental efforts to non-driving tasks, or operating mobile devices by hand [17]. Among the three distraction types, visual-manual combined distraction has the highest crash risk ratio [17]. Today's smart phone plays the role of a micro computer with rich content rather than a phone for calling and texting. It caused more complex distraction [18]. Using smart phone Apps while driving creates visual-manual tasks typically, which require drivers to look at the graphic user interface and touch the screen to operate. Although off-road glances shorter than 2 second have been shown only increased crash risk slightly, glances over 2 seconds have increased the risk much higher [19]. Previously, texting while driving had been blamed in many publications due to its easiness of generating off-road glances longer than 2 seconds; however, rich contents in smart phone Apps today have lifted up the frequency of long off-road glances greatly.

C. *Natural User Interface for Reducing Distraction*

Natural user interface (NUI) can provide tactile interaction, speech interaction and kinect interaction between human and machines. It provides great learnability through being in line with natural human behavior [20]. Without occupying driver's visual resource (the most important resource while driving), speech interaction has a huge potential on in-vehicle application. Previous study showed that speech interaction could reduce driver distraction significantly as well as improve driving performance while selecting music, making calls and using navigation systems [21]. But according to the depth of speech content, command-based interaction and conversation-based interaction have different effect on reducing driver distraction [22]. As described above, only limited car models on the market had already integrated speech interface into their IVIS. Comparatively, hundreds of speech recognition Apps could be downloaded to mobile devices instantly today. The major functions of these Apps include speech-to-text translation, command-based operation, and conversation-based operation. Representatives of speech recognition service providers who are popular in Chinese market include Apple's Siri [23] and iFlyTek (a Chinese corporation)'s iFly [24].

III. User Interface Design and the Prototype

A. *Driver's Use of Siri as an Example*

Although speech interaction itself is mainly cognitive demanding without generating visual and manual workload, the entire process from start the speech interaction until end usually does. Currently, speech interface on most mobile devices requires two operations generated visual and manual distraction while driving: 1) drivers have to reach out to their devices and push a physical or graphic button (PTT) to activate the listening mode of the speech interface; 2) drivers may have to glance at the display of the devices to check the output of speech recognition.

As an original App on iPhone (one of the most popular mobile devices in the world), Apple's Siri defined the "Home" key of the device as its PTT button, which made Siri more convenient compared to other aftermarket Apps with speech interaction function. Figure 1 shows the regular process to complete a LBS task via Siri: first, pick up the device and push the PTT button; second, speak to the device to input speech information; then, hold the device and listen to an audio alert when Siri finished searching; last, glance over the visual outputs and select a satisfied result. It can be seen that all the four steps are manual demanding and the last step is visual demanding in addition.

Figure 1. Local search with Apple's Siri on iPhone 5s

B. *New User Interface Design*

To reduce manual and visual distraction in speech interaction, we designed a new interface which was adaptive to Siri (as a representative of speech interaction Apps) and the LBS task (as a typical interaction between drivers and mobile devices during driving) in this study. As illustrated in Figure 2, the new interface included a Bluetooth module mounted on the steering wheel to receive drivers' PTT operation and speech input remotely from their mobile device, and a head-up display (HUD) unit on the windshield to present Siri's output of searching results visually. The Bluetooth module communicated with Siri via the Bluetooth connection on iPhone and equipped a PTT button, a microphone and a speaker. Using the back of steering wheel as space for hands interaction and combined HUD has been strongly recommended to reduce drivers' hands-off-wheel and eyes-off-road [25]. In our design, the Bluetooth module was mounted on the front of the steering wheel, which allowed drivers to use their thumbs to push the PTT button easier.

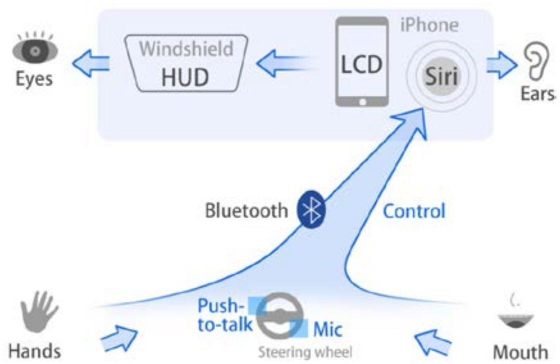

Figure 2. Interaction model of the new user interface

The HUD unit was an easy setup including a small piece of semi-transparent film on the windshield to project iPhone's screen, and a dashboard mount for the mobile device, as shown in Figure 3. In the new voice interaction loop for a LBS task, drivers would first push the PTT button on steering wheel to activate Siri; then speak naturally without taking hands off the wheel; wait until Siri find answers and give an audio alert via the speaker on steering wheel; last, look at the HUD area on the windshield to check results, select a destination and tell Siri the name of the destination by the presenting sequence (e.g., I want to go to the third one). At the end, Siri displayed the route in HUD and navigated by audio instructions. Although drivers' glances to the HUD unit could also be identified as "attention-off-road", the time and spatial cost of moving eyes from road to the display of visual output has been reduced much compared to the original mode. In general, interaction with Siri via the new interface cost very little manual operation and less visual resource, which narrowed the gap of manual and visual demand between single driving tasks and dual tasks with mobile device use.

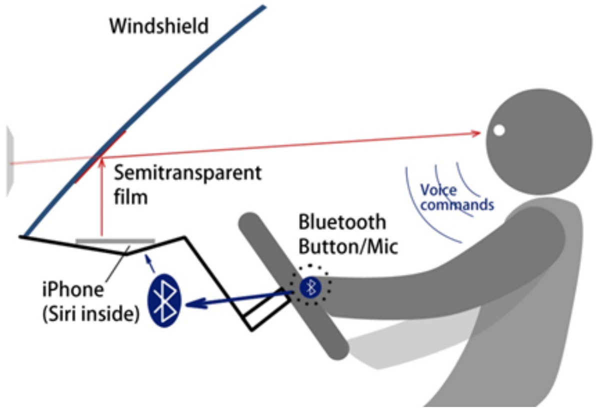

Figure 3. Sketch of the interface with user context

C. Prototype Development

We prototyped the Bluetooth module with a ready-made Bluetooth chip from a Bluetooth headset, and resealed it after we connected the audio output part to a mini speaker. Benefited from its small size, the Bluetooth module could be flexibly mounted on the steering wheel based on drivers' preference. Once paired an iPhone (with operating system of iOS 7) with the Bluetooth module, Siri can be simply activated by pushing the PTT button on the steering wheel (See Figure 4).

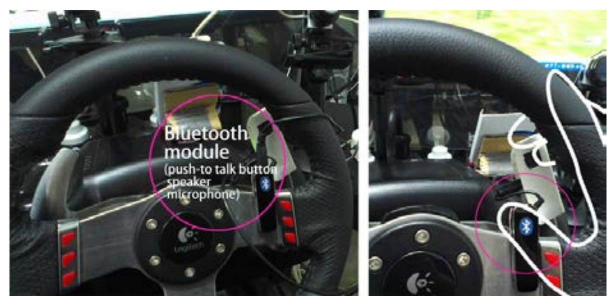

Figure 4. Prototype of the Bluetooth module

Another part of the prototype was the HUD unit, which displayed a modified mirror graphic of iPhone's display with appropriate font size and graphic contrast. As illustrated in Figure 5, a piece of semi-transparent film about in the same size of iPhone 5s was stuck on the windshield of a driving simulator, slightly right to the steering wheel. The mobile device connected to the Bluetooth module was laid on the dashboard and faced to the HUD unit. Graphics and texts were designed as mirror images on the mobile device, and then easily reflected to the HUD. A dark background, bright graphics and larger text fonts were designed for the HUD to highlight visual output (See Figure 6).

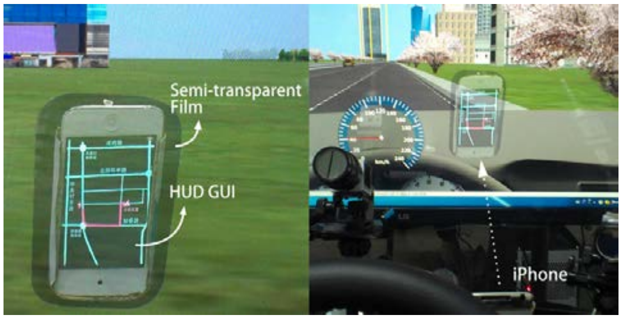

Figure 5. Prototype and layout of the HUD unit

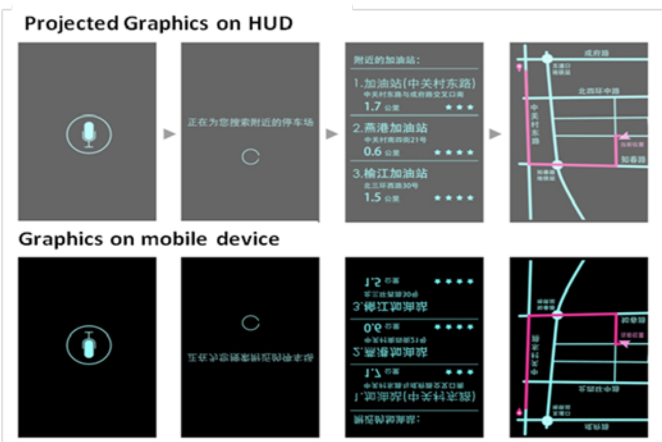

Figure 6. Mirror images on the mobile device and HUD

IV. Evaluation Method

Driving performance, Peripheral Detection Task (PDT) performance, LBS task performance and participants' subjective user experience assessment of the prototyped interface were evaluated through a driving simulator study conducted in Beihang University, Beijing, China.

A. Participants

Twenty four young adult drivers aged from 20 to 29 with an average of 24.2 (SD=2.84) were recruited by Internet advertisement in Beijing. Participants were required to be active drivers and mobile phone users. They also need to have a good health condition on the experimental day and a safe driving history (record free of accidents) for the past year. A Compensation of 100 Chinese Yuan (CNY) was provided for their participation.

B. Apparatus

Driving task was completed on a fixed base driving simulator with three wide-screen LCD displays. Front, left, right roadway and a rear view mirror was presented virtually on the LCD displays with approximately 143º field of view horizontally. The simulated roadway and traffic scenarios were generated by UC-Win/Road Ver.8 Standard (FORUM8, Tokyo, Japan) with a refreshing rate about 20 Hz. The mobile device used in this study was a brand new Apple iPhone 5s (screen size: 4 inch; resolution: 1136 x 640) operated by iOS 7 (Apple Inc., Cupertino, CA).

C. Peripheral Detection Task (PDT)

The Peripheral Detection Task, which has been validated as a good tool, is a method for measuring the amount of driver mental workload and visual distraction while driving [26, 27, 28]. The task presents random targets in driver's peripheral view. As becoming distracted, drivers respond slower and miss more PDT targets. Figure 7 illustrates the configuration for PDT task used in this study. Two LED arrays were placed on the windscreen at a horizontal angle of approximately 11 to 23 degrees to both the left and right of the driver's forward view and at a vertical angle of approximately 2 to 4 degrees above the horizon. The left or right LED array was randomly illuminated (in red color) every 3-6 seconds. It lasted for 2 seconds. Participants were asked to press a green round button attached on the steering wheel once they saw the LED array was illuminated. Response time was defined as time from the onset of LED illumination to the press of response button. Responses over 2 seconds would be considered a missed event.

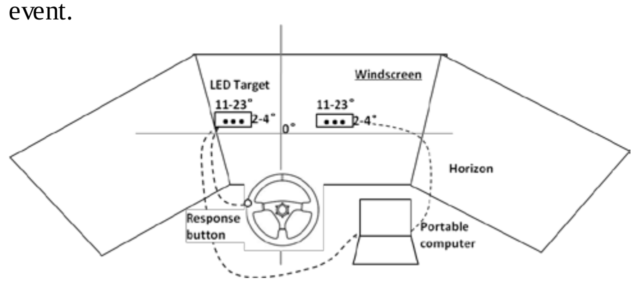

Figure 7. Illustration of the Peripheral Detection Task used in the experiment (inspired by [26])

D. Procedure

Participants reviewed and signed a consent form upon arrival. Then they were trained well to use Siri under three modes to complete a series of LBS tasks while sitting in the simulator without driving. The three modes included an original setting of Siri (pick up and hold the phone, PUP), using the Bluetooth module only for speech input and audio output (BT+AU), and using both the Bluetooth module and HUD for speech input and visual aided output (BT+HUD). Once participants felt confident to use Siri, an 8km driving exercise on highway was conducted to help participants to get used to drive in the simulator. At least one practice of each Siri mode while driving was instructed during the exercise session. The formal test was run on a two-way six-lane urban road. A low to moderate traffic density (500 vehicles per lane per hour) and moderate speed (50 km/h to 65 km/h) were designed for both directions. Participants were instructed to drive on the central lane by following a leading car with a constant speed of 60 km/h.

Eighteen LBS tasks, 3 without PDT and 3 with PDT for each mode, were distributed with intervals of 60 seconds (for PUP) or 90 seconds (for BT+AU and BT+HUD) along the test. Each LBS task was composed by an audio instruction of searching a specific service (e.g., gas station, restaurant, hotel. etc.) nearby, using a specific mode of Siri, and selecting a destination with a specific criteria (e.g., the nearest). The presenting sequence of experimental conditions were: 2 minutes pure driving, 3 PUP tasks, 3 BT+AU tasks, 3 BT+HUD tasks, 2 minutes pure driving with PDT, 3 BT+HUD tasks with PDT, 3 BT+AU tasks with PDT and another 3 PUP tasks with PDT. Visual output on both HUD and iPhone showed three searched results in one page. Audio output broadcasted results one by one. All destinations were located in the first three results. To ensure the consistence of Siri's searching results, we have tested more than 30 destinations by five volunteers on the driver seat of the simulator. Finally chose the most stable 18 destinations (always presenting the same results) to be used in the experiment.

When finished driving, participants were asked to fill in a questionnaire to rate how convenient to use, how distractive, and future willingness to use of the three modes by 7-point Likert Scales.

D. Data Analysis

Comparisons of the three Siri modes on LBS task performance, PDT response time, driving performance and user experience were computed with IBM SPSS 19 (IBM Co., Foster City, CA) using a repeated measure General Linear Model (GLM). Greenhouse-Geisser correction would be applied when sphericity could not be assumed in GLM. Pairwise tests (with a LSD adjustment) were computed for significant results in GLM. Statistic for a non-parametric variable, the success rate to response PDT was conducted by Friedman test and Wilcoxon rank tests to instead of repeated measure ANOVA and pairwise test in GLM. Significance reported at $p<0.05$.

V. Results and Discussion

A. LBS Task Performance

Task Completion Time: The time from a participant start to use Siri (the end of the audio instruction of a LBS task) until participant select a destination. Average of valid trials on each interface mode was computed. The main effect of interface mode was found strongly significant (F (2, 46) =121.80, $p<0.001$). Pairwise tests showed that the original mode, picking up the phone (PUP) was the quickest one to finish LBS tasks, slightly faster than speech input and visual output (BT+HUD) mode ($p<0.01$). But both of the modes above are much faster than the speech input and audio output (BT+AU) mode ($p<0.001$). The presentation of PDT doesn't impact drivers' LBS task performance (F (1, 23) =0.859, p=0.364). Figure 8 presented data in details and error bars. Result suggested that drivers can complete the secondary task with visual aids faster than with only audio aids; holding the phone on hand is still quicker than looking at HUD display to complete a task.

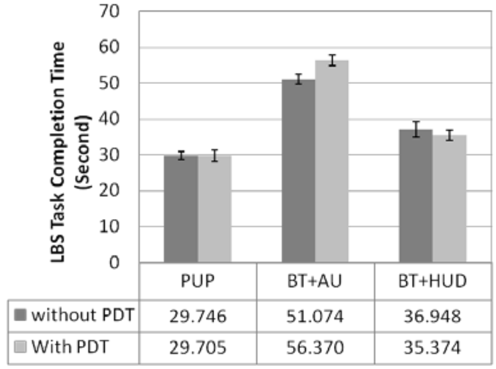

Figure 8. Mean task completion time to finish a LBS task

B. PDT performance

Data recording errors of PDT were happened to two participants, which left 22 subjects for the analysis of PDT performance.

Success rate: the success rate was defined as the percentage of successful responses (one minus missing rate). Since this ratio measure often clustering near 100%, giving success rate distributions a strong negative skew. Therefore, parametric statistics such as the t-test and repeated-measures ANOVA are not appropriate. We employed corresponding non-parametric tests, the Wilcoxon rank tests and the Friedman test for this measure. Statistics found a significant difference of PDT success rate between interface modes (X^2 (2) =14.88, $p<0.001$). Pairwise comparisons showed that drivers' successful responses to PDT under the picking up (PUP) mode was significantly fewer than the speech input audio output (BT+AU) mode (Z = -3.17, p <0.01) and the speech input visual output (BT+HUD) mode (Z = -2.86, p <0.01). However, the BT+AU mode and the BT+HUD mode did not has significant difference (Z = -1.40, p =0.161). Result suggested that objects in the peripheral view are more difficult to be detected if drivers use mobile phone by their hands; both audio and HUD visual presentation of searching results are better.

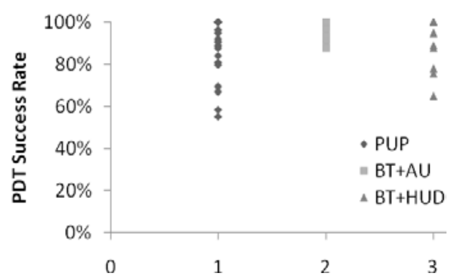

Figure 9. Rate of successful responses to PDT stimuli while driving

Response time: participants' response time to PDT stimuli was found significantly different between interface modes (F (2, 42) =11.187, $p<0.001$). Pairwise tests showed that under both the BT+AU mode and BT+HUD mode, participants had responded to PDT stimuli faster than under the PUP mode ($p<0.001$ and $p<0.05$, respectively). Response time under the BT+AU mode was also shorter than the BT+HUD mode. Figure 10 presented data in details and error bars. Result suggested that drivers will detect objects in their peripheral view slower when hold mobile phone on hand; audio output helps them to detect quicker.

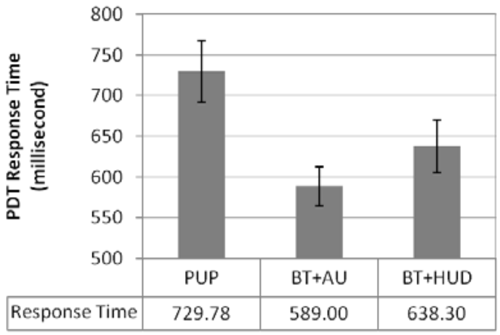

Figure 10. Mean response time to PDT stimuli while driving

C. *Driving performance*

Longitudinal control: participants' speed variation (calculated as the standard deviation of longitudinal speed) in dual-task situation, conducting LBS tasks while driving was found significantly different between interface modes ($F(1.57, 36.05) = 7.655$, $p<0.01$, with Greenhouse-Geisser correction). Pairwise tests showed that the speed variation under the BT+AU mode was significantly larger than and PUP mode ($p<0.05$) and the BT+HUD mode ($p<0.001$). However, no difference was found between the PUP mode and the BT+HUD mode. Neither the effect of PDT condition nor the interactive effect between PDT and interface mode was found significant on speed variation. Mean speed was not found significant different on any condition. Figure 11 presented data in details and error bars. Result suggested that drivers have more flexible control of speed with audio output.

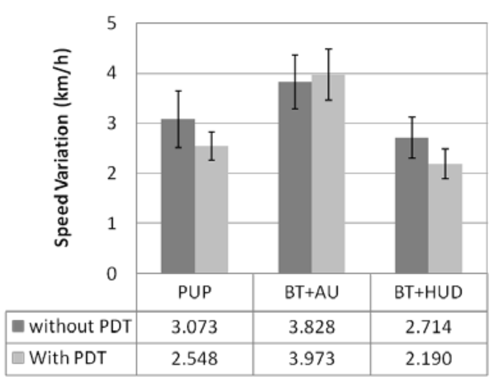

Figure 11. Mean logitudinal speed variation during LBS tasks

Lateral control: participants' lateral variation (calculated as the standard deviation of lane position) in dual-task situation was found significantly different between interface modes ($F(1.29, 29.68) = 7.492$, $p<0.01$, with Greenhouse-Geisser correction). Pairwise tests showed that drivers' lateral variation under the PUP mode was significantly larger than and BT+AU mode ($p<0.01$) and the BT+HUD mode ($p<0.01$). However, no difference was found between the BT+AU mode and the BT+HUD mode. Neither the effect of PDT condition nor the interactive effect between PDT and interface mode was found significant on lateral variation. Figure 12 presented data in details and error bars. Result suggested that driver's lane keeping capacity will be suffered more when hold mobile phone on hand.

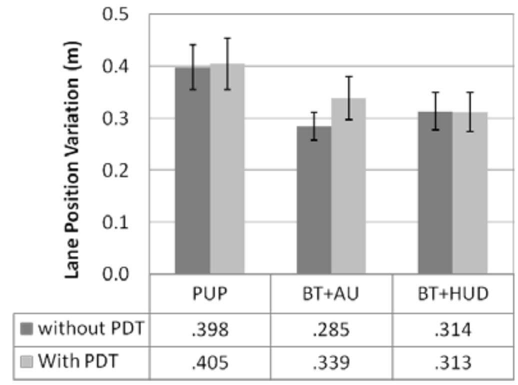

Figure 12. Mean lane position variation during LBS tasks

D. *User Experience*

How convenient: a 7-point rating of how convenient to use the interface while driving; 1 refers to very inconvenient and 7 refers to very convenient. The main effect of interface mode was found significant ($F(2, 46) = 19.776$, $p<0.001$). Pairwise tests showed that participants felt both BT+HUD and BT+AU were more convenient to use while driving compared to PUP ($p<0.001$ for both). However, no significant difference was found between BT+HUD and BT+AU. Figure 13 presented detailed data and error bars.

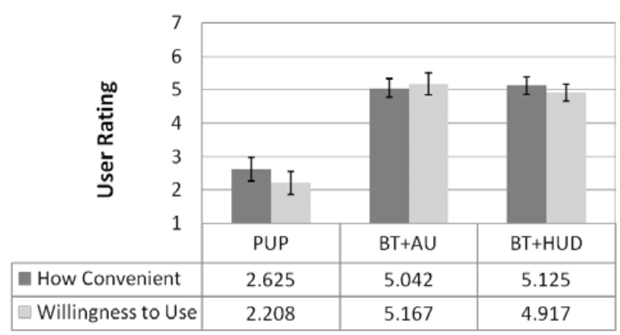

Figure 13. User ratings of interface convenience and willingness to use in the future

Willingness to use: a 7-point rating of participant's future willingness to use about an interface; 1 means not willing to use at all and 7 means very willing to use. The main effect of interface mode was found significant ($F(2, 46) = 22.375$, $p<0.001$). Pairwise tests showed that participants were willing to use both BT+HUD and BT+AU while driving more than PUP in the future ($p<0.001$ for both). But no significant difference was found between BT+HUD and BT+AU. Figure

13 presented detailed data and error bars. Result suggested that drivers felt more convenient and more willing to use the speech input interface.

How distractive: a 7-point rating of how distractive to use the interface while driving; 1 refers to not distractive at all and 7 refers to very distractive. The main effect of interface mode was found significant (F (2, 46) =28.045, p<0.001). Pairwise tests showed that participants felt PUP was much more distractive compared to BT+HUD and BT+AU (p<0.001 for both). No significant difference was found between BT+HUD and BT+AU. Figure 14 presented detailed data and error bars. Result suggested that drivers felt less distractive to use the speech input interface while driving.

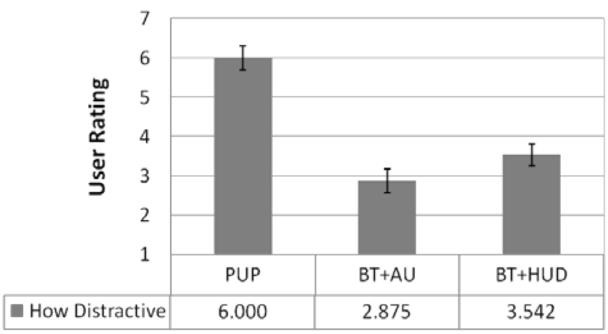

Figure 14. User rating of how distractive to use the interface while driving

VI. DISCUSSION

Objective and subjective assessment gained from the driving simulator experiment supported that the speech input and visual output interface designed in this study was an optimistic solution to mitigate driver distraction caused by speech interactions with mobile devices while driving. Picking up the phone and hold it to complete LBS task has a little benefit, e.g., cost shorter time to complete the LBS task; however, it suffered the PDT performance and driver's lateral control much. From another side, although the HUD interface of visual output shows no significant advantages on most of the measurements, even slightly disadvantageous for some measurement compared to audio output, the obviously shorter LBS task completion time of BT+HUD mode made it the best solution.

The LBS task designed in this study was a simple one. Interactions with speech interfaces like Siri in the real life could be much more complex, in that way audio output would become fairly cognitive demanding, which suffers driving performance quickly. Therefore, the combined interface of remote speech input via Bluetooth and visual output via HUD (BT+HUD) developed by the authors has great potentials to make up drawbacks of both the original mode of using mobile devices in car and the improved mode of using only Bluetooth module.

VII. CONCLUSION

In this paper, we presented a driver-friendly interface for using driving assistance Apps with speech interface on mobile devices while driving. The interface included a Bluetooth module mounted on the steering wheel to activate speech interaction remotely, and a HUD unit on the windshield to provide visual aid remotely. The interface was designed to reduce extra manual and visual workload generated by using the current speech interaction mode on most mobile devices. Drivers' performance on the new interface and subjective evaluation were tested through a driving simulator experiment. Results showed that the new interface designed in this study had reduced driver distraction, increased efficiency and usability. It can contribute to the design and development of both manufactures' IVIS integration for mobile devices and the third party's aftermarket accessories for in-vehicle mobile use.

Future works on running more subjects and exploring the impacts on drivers' visual attention and other dependent variables were expected.

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