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ATTENTIONAL ISSUES WITH SUPERIMPOSED SYMBOLOGY: FORMATS FOR SCENE-LINKED DISPLAYS

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INTRODUCTION

The head-up display (HUD) is a collimated, transparent display medium upon which graphical information, or superimposed symbology, can be presented. Since it is transparent, the main feature of the HUD is that it is located above the instrument panel, allowing the pilot to simultaneously view the out-the-window scene and the superimposed symbology, without refocusing the eyes or making large eye-scan movements. HUDs have been shown to be a superior presentation method for flight path symbology over that of traditional flight director displays (Boucek, Pfaff & Smith, 1983).

Recent studies, however, have shown that there are specific performance problems associated with HUDs. During simulated landing with superimposed HUD symbology, Wickens and Long (1994) showed that, although the HUD symbology supported precision landing, the pilot was not necessarily simultaneously processing the symbology and the out-the-window scene. Pilots took 2.5 seconds *longer* to respond to an unexpected runway incursion when the symbology was presented head-up than when head-down. This extends and replicates previous work (e.g., Weintraub, Haines & Randle, 1984) showing that superimposed HUD symbology may lead to attentional tunneling and inefficient processing of the out-the-window scene.

Attentional tunneling with superimposed symbology has also been demonstrated in continuous flight simulation tasks (Foyle, McCann, Sanford & Schwirzke, 1993; McCann & Foyle, 1994). In these studies, subject pilots were instructed to maintain 100 ft altitude while simultaneously flying a flight path, designated by environmental objects (pyramids forming a path on the ground), in the presence of vertical and lateral turbulence. In the superimposed HUD symbology condition, a digital readout of current altitude (in ft) was graphically superimposed on the graphical visual simulation. Altitude maintenance and flight path maintenance were measured by root mean square error (RMSE) deviations from 100 ft altitude, and lateral offset from the ground path, respectively. Not surprisingly, the superimposed digital altitude display improved altitude maintenance, compared to a condition without an altitude display where only existing environmental cues (e.g., surface grid and pyramid size) were available to maintain altitude. The ability to follow the ground flight path, in contrast, showed an opposite pattern: Flight path maintenance was worse when the superimposed digital altitude was present compared to the condition with no altitude display. Attentional tunneling, the inefficient joint processing of the superimposed symbology and the out-the-window scene, was demonstrated by the presence of this performance tradeoff: The superimposed altitude symbology improved altitude maintenance control, but led to poorer control of the out-the-window flight path.

In operational usage, superimposed symbology on a HUD is mostly presented at a fixed, specific location on the HUD combiner. For example, in one HUD manufacturer's implementation, the air speed and ground speed are digital numbers presented in the lower left of the display. (Exceptions to this are such symbologies as the artificial horizon, the flight path vector and the symbolic runway, all of which move on the combiner glass so as to maintain conformal, visual overlays with the actual horizon, the aim point, and the actual runway, respectively.) As the pilot views the HUD, the symbology stays in a fixed location, while the world scene behind it pitches, yaws, and rolls in response to aircraft motion. McCann, Lynch, Foyle and Johnston (1993) measured the time it takes to switch between the world scene and the superimposed HUD symbology. They found that differential motion between the superimposed HUD symbology and the out-the-window scene led to increased attentional switching time, and concluded that this differential motion may be the primary driver behind attentional tunneling.

If the primary cause of attentional tunneling is differential motion between the HUD symbology and the world, then removing the differential motion cues should minimize the attentional tunneling problem. One design option that achieves this goal is to replace conventional HUD symbols with virtual symbols that appear to be physically part of the world (Foyle, Ahumada, Larimer & Sweet, 1992; McCann & Foyle, 1994). Although rendered in graphics on the HUD, these "scene-linked" symbols are drawn, and move, as virtual objects in the out-the-window scene. As the aircraft moves through the world, the scene-linked symbols undergo the positional visual transformations as real objects. There are no differential motion cues to cause the visual system to interpret the virtual symbols as separate from the world. In the absence of these cues, attentional tunneling should be prevented, enhancing the ability to process scene-linked HUD symbology in parallel with real-world information.

SCENE-LINKED SYMBOLOGY

Scene-linked symbology can take three forms. *Scene Enhancements* entail the outlining in symbology of existing objects. One HUD manufacturers' symbolic runway, in which a HUD runway outline overlays the actual runway, is an example. *Scene Augmentations* represent the addition of virtual, non-real, three-dimensional objects drawn on the HUD as if they existed at a location in the real world. An example would be the depiction on a HUD of "virtual traffic lights", which could inform the pilot as to clearance to cross an active runway during taxi. *Virtual Instruments* are the depiction of aircraft instrumentation and aircraft data values drawn on a "virtual billboard". An example of this might be a digital/tape readout of actual and current glideslope on a virtual billboard to the side of the aimpoint of your cleared runway.

The goals of the present experiment were twofold. The first goal was to test whether scene-linked symbology minimizes attentional tunneling. As mentioned previously, scene-linked symbology removes the differential motion between the superimposed HUD symbology and the out-the-window scene. From the results of McCann, Lynch, Foyle and Johnston (1993), it was hypothesized that removing differential motion cues via scene-linked symbology would alleviate attentional tunneling, as evidenced by the absence of the altitude/path maintenance performance tradeoff. To evaluate this hypothesis, two symbology types were tested, scene-linked symbology and superimposed symbology. It was predicted that there would not be a performance tradeoff with scene-linked symbology, rather, it would improve altitude maintenance, without a corresponding deterioration in ground flight path maintenance. For superimposed symbology, it was predicted that the present experiment would replicate previous results and yield a performance tradeoff: Superimposed symbology would improve altitude maintenance, but would result in worse ground flight path maintenance.

The second goal was to explore and extend the generalizability of previous studies (Foyle, McCann, Sanford & Schwirzke, 1993; McCann & Foyle, 1994) to include different display formats. To date, all superimposed altitude displays have been presented in digital format. Research has indicated that analog clock display formats may be processed more easily than digital values, requiring fewer direct visual fixations and less attentional effort (Weinstein, Ercoline, Evans & Bitton, 1992). This raises the possibility that attentional tunneling was a result, not of the superimposition of the symbology at a fixed screen location, but of the high visual/attentional processing load imposed by digital formats. Therefore, the performance tradeoff could be the result of either: 1) The increased visual/attentional processing required with digital superimposed symbology; or, 2) The superimposition of the display at a fixed location, and hence, differential motion between the symbology and the world. The present experiment distinguishes between two hypotheses by testing both digital and analog superimposed symbology. The first hypothesis predicts that the performance tradeoff would obtain with digital superimposed symbology, but not with analog superimposed symbology. The second hypothesis predicts that there would be no effect of the digital/analog clock format on the performance tradeoff, since differential motion is unaffected by format.

EXPERIMENTAL TEST: SCENE-LINKED VIRTUAL INSTRUMENT SYMBOLOGY

A within-subject design was used to evaluate the effects of HUD symbology type. Five conditions of HUD symbology formats were tested. Altitude information was presented (see Figure 1) in the format of: 1) Superimposed digital (digital value superimposed at a fixed location on the screen); 2) Superimposed analog (analog clock format superimposed at a fixed location on the screen); 3) Scene-linked digital (digital value scene-linked into the simulation scene); 4) Scene-linked analog (analog clock format scene-linked into the simulation scene); and, 5) No altitude readout (control condition with no altitude display). All superimposed HUD symbology conditions were simulated in graphics, with the graphical symbology superimposed on the graphical world simulation. There were a total of 90 trials (18 replications of the 5 HUD symbology conditions). Each replication consisted of the HUD conditions presented in random order. The first 8 replications served as practice trials, with analyses conducted on the remaining 10 replications.

SIMULATION AND PROCEDURE

A Silicon Graphics Onyx RE2 computer was used to present the flight simulation and to collect data. The simulations were viewed on a high-resolution 19-inch color monitor from a distance of 65 cm. The flight simulation was controlled with a spring-centered joystick built into the right arm of the participant's chair.

The flight simulation, a simple kinematic model, did not pitch up or down when climbing or descending to ensure that the heading information in the virtual environment would be visually available at all times. Roll was accurately depicted. The environment contained a blue sky, with a white regular grid superimposed on the green ground.

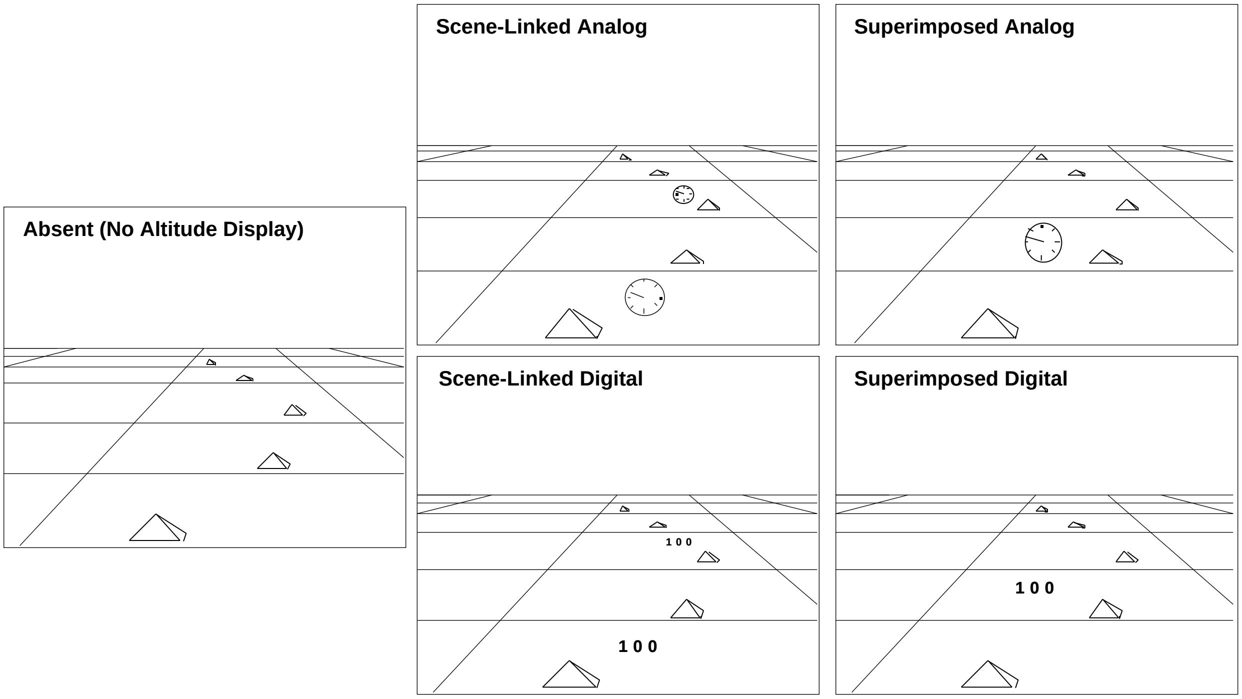

Figure 1. **Schematic drawings (not to scale) of the five HUD symbology conditions (as labeled).**

Participants followed one of eight paths on each trial. Each path was marked by a series of 37 brown pyramid-shaped objects that were 24 ft x 24 ft at the base, and 6-ft high (scaled in the virtual environment). The pyramids were positioned 330 feet apart on the ground. Each successive pyramid was angled away, either right or left, from 15 to 30 degrees, to form a meandering path. Forward speed was 160 kts, with each path requiring approximately 55 secs of simulated flight. One of eight paths were randomly assigned to each trial, with the restriction that each path be used a minimum of eleven times for each participant. Random vertical (altitude) and lateral (path) turbulence (sum of sines) was present during all trials (uncontrolled adjusted RMSE were 21.8 ft, and 35.9 ft, respectively for altitude and path). These conditions were chosen to replicate previous simulation conditions, and to provide a relatively high-workload flight environment. The graphics and data collection were updated at 12 Hz.

The digital format display consisted of the altitude (to the nearest ft) in a custom LED-like font. The analog display had a yellow clock face, containing 8 white tick marks indicating 25 ft intervals and a single black bar indicator. The 9 o'clock position indicated an altitude of 100 ft, with 6 and 12 o'clock respectively representing 50 and 150 ft (after Weinstein, Ercoline, Evans & Bitton, 1992). In the superimposed HUD conditions (superimposed digital, superimposed analog), the altitude information was at a fixed screen location, centered along the width of the screen, and positioned two-thirds of the way up between the bottom of the screen and the horizon line. The digital indicator formed a rectangle 1.40 cm wide x 0.75 cm high, with the numbers appearing in black. The analog clock display was 1.70 cm in diameter. In the integrated HUD conditions, the altitude indicators were virtually placed on the ground, positioned equidistant between each second pair of pyramids. Scaled to the virtual environment, each display, digital and analog clock, was 15 ft high (see Figure 1).

Fourteen right-handed male subjects, with normal- or corrected-to-normal eyesight were tested. Participants were paid for the one 2.5-hour session, and no previous flight experience was required. Participants were instructed to simultaneously maintain altitude at 100 ft, and follow the ground path as closely as possible. Instructions to the participants stressed the need for accuracy. At the end of each trial, participants were given verbal feedback concerning their performance. Each flight began with 9 sec of forward flight at the assigned altitude of 100 ft and without turbulence to allow the subjects to "calibrate" themselves to the visual environmental altitude cues. Turbulence and data collection began at the first path pyramid.

The dependent measures were RMSE altitude and RMSE heading. Altitude errors were determined by measuring vehicle distance (ft) from the assigned altitude (100 ft). Path errors were determined by measuring the lateral vehicle distance from the closest straight-line segment in the path, as they flew the virtual environment.

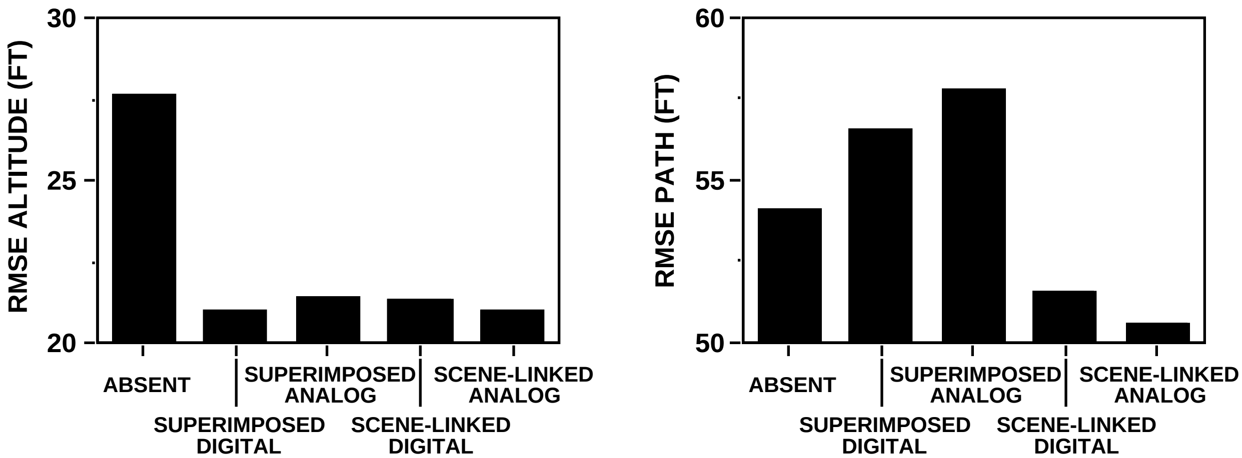

Figure 2. **Results of experimental test: Effects of HUD altitude symbology absence, superimposed digital symbology, superimposed analog clock symbology, scene-linked digital symbology and scene-linked analog clock symbology on RMSE Altitude (left) and RMSE Path right).**

RESULTS AND DISCUSSION

Separate analyses of variance (ANOVAs) were conducted on the RMSE altitude and path results. Effects involving replication were not significant for either measure. For altitude maintenance (Figure 2, left panel), display condition (the 5 conditions) had a reliable main effect on altitude performance ($F(4,52) = 22.29$, $p < .0001$). This was attributable to improved altitude performance in the four conditions when HUD altitude information was present than when absent ($F(1,13) = 47.57$, $p < .0001$). This finding is not surprising in that it shows that subjects are able to use effectively the altitude readout displays for altitude maintenance. Altitude maintenance was equally good independent of the type of altitude display present, whether superimposed or scene-linked, or digital or analog (all planned comparisons, $F < 1$). The improvement in altitude with superimposed digital information compared to the condition in which there is no explicit altitude display, other than pictorial altitude cues, replicates previous studies (Foyle, McCann, Sanford & Schwirzke, 1993; McCann & Foyle, 1994).

For flight path maintenance, display condition also had a reliable main effect on RMSE path performance ($F(4,52) = 6.57$, $p = .0002$). Path performance in the two superimposed conditions was worse than when altitude information was absent ($F(1,13) = 4.43$, $p = .055$). (The superimposed digital vs. analog conditions did not differ statistically, $F < 1$.) Taken with the altitude maintenance results, the results of the superimposed HUD conditions replicate previous studies (Foyle, McCann, Sanford & Schwirzke, 1993; McCann & Foyle, 1994). For the superimposed HUD conditions, there is an altitude/path maintenance performance tradeoff: The superimposed HUD altitude information improved altitude maintenance performance, but was associated with poorer path performance. The absence of an effect of digital/analog format rules out the hypothesis that the attentional tunneling effects were due to format and related processing effort issues: Attentional tunneling is likely due to the differential motion of the out-the-window scene and fixed-screen location superimposed symbology.

In contrast, the two scene-linked conditions show a different pattern: Relative to the control condition with no explicit altitude display, scene-linked HUD symbology yielded *improved* path maintenance performance ($F(1,13) = 5.58$, $p = .035$). (The scene-linked digital vs. analog conditions did not differ statistically, $F < 1$.) That is, the scene-linked altitude displays not only did not lead to an altitude/path maintenance performance tradeoff, like that seen in previous studies, but rather improved *both* altitude maintenance and flight path maintenance performance. This finding replicates, in principle, that reported in McCann and Foyle (1994): Scene-linked symbology may lead to efficient simultaneous visual/cognitive processing of both the HUD symbology display *and* the out-the-window scene. This finding of improved path maintenance performance is potentially important: Not only did the scene-linked Virtual Instruments symbology alleviate attentional tunneling, but an added characteristic emerged -- improved performance on the out-the-window flight path maintenance task. This added "bonus" of improved processing of the out-the-window scene with scene-linked symbology merits further study. The remaining part of this paper focuses on an application of scene-linked symbology: low-visibility surface operations.

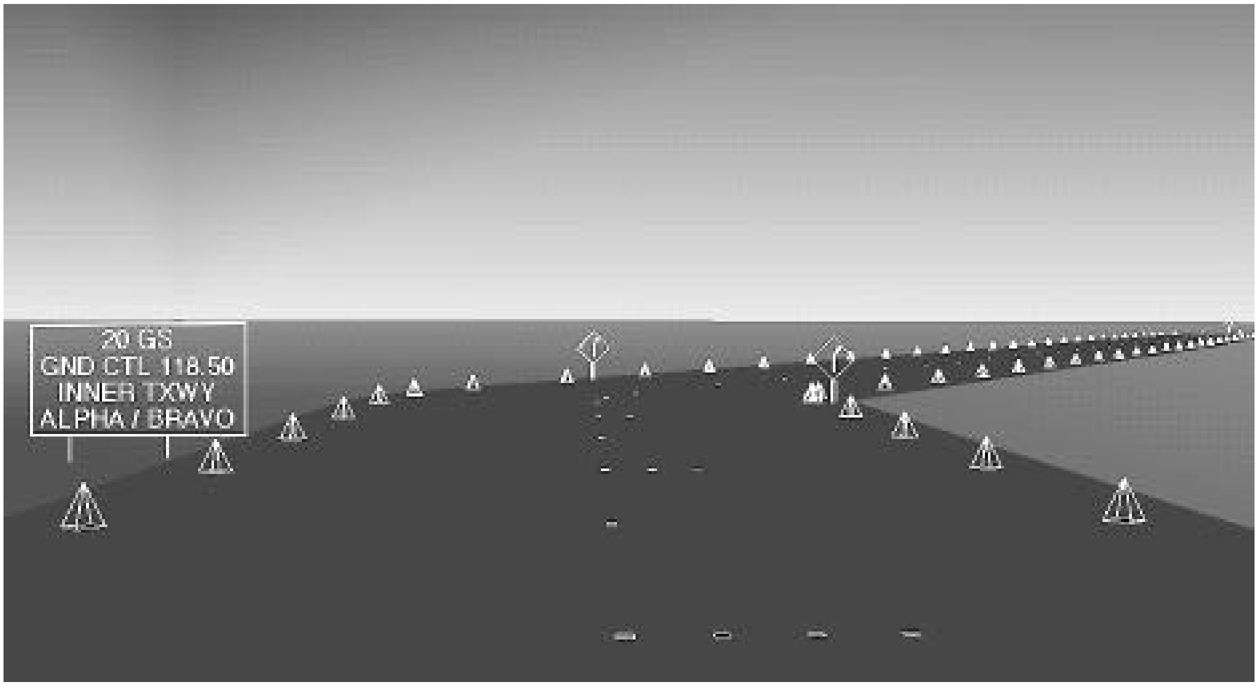

Figure 3. **Scene-linked HUD symbology for taxi and surface operations. Symbology (shown in white) includes Virtual Instruments (billboard aircraft instrumentation and location information) and virtual Scene Augmentations (edge cones, turn signs and "countdown" warnings).**

APPLICATION: SCENE-LINKED SYMBOLOGY FOR LOW-VISIBILITY SURFACE OPERATIONS

Design solutions are only useful insofar as the technology is available to implement them. The ability to generate this and other scene-linked symbology requires an advanced display medium, such as a HUD, an accurate database, and a highly accurate positioning system, such as the Differential GPS (DGPS) system. Our research suggests that linking HUD symbology to the outside scene in this "scene-linked" fashion enhances parallel processing of symbology and the forward visual scene. Taxi and other surface operations are a particularly attractive environment for scene-linked HUDs. Today, pilots are given little or no explicit information concerning their current position, and routing information is limited to air traffic communications (ATC) and paper airport charts. Under low-visibility conditions, pilots can easily become spatially disoriented, leading to time-consuming interactions with ATC, and reductions in taxi speed. In Figure 3, we present a candidate scene-linked HUD symbology taxi display to alleviate these problems. The candidate HUD symbology contains two types of scene-linked information: Virtual Instruments (aircraft communication information and current location displayed on a virtual "billboard"), and Scene Augmentations (taxiway edge markers pictorially augmenting the scene).

The Virtual Instruments "virtual billboard" to the left of the taxiway includes aircraft communication status information and ground location. The top line contains the aircraft's current ground speed (20 KTS, "20 GS"). This is a dynamic readout and would change as appropriate. Similarly, the ground control radio frequency setting is shown ("GND CTL 118.50"). The other two lines on the virtual billboard represent the aircraft's current airport location. The "Current, Last/Next" format represents current runway or taxiway segment ("Inner Taxiway"), the last intersection passed ("Alpha"), and the next intersection upcoming ("Bravo"). The example shows that this aircraft is on the Inner Taxiway, past Alpha, and before Bravo taxiway. The pictorial Scene Augmentations shown include visual information that would aid the pilot in following the taxiway clearance and completing turns. Vertical side cones on the side of the commanded taxiway path depict the ATC cleared route on the HUD in superimposed symbology (as in "Pink 5" at Chicago O'Hare). These markers are conformal and are a virtual representation of the cleared taxi route on the HUD. The side cones and the centerline markings are shown repeated every 50 feet down the taxiway. The vertical development and constant spacing should yield increased capability for estimating ground speed, drift, and look-ahead capability for turns (Johnson & Awe, 1994). Turn "countdown" warnings are shown in which each turn has countdown (4, 3, and 2) centerline lights that are (300, 200, and 100 feet, respectively) before each turn. This gives added distance cues for the turn. The virtual turn signs (with the arrows) give an added cue to the turn. In addition, the angle of the arrow on sign represents the true angle of the turn (i.e., 30 deg right for a 30 deg right turn). All of the HUD symbology is scene-linked, which should enable the pilot to process the symbology efficiently with other traffic, including possible incursions. This and other candidate scene-linked HUDs are currently under test in a high-fidelity part-task simulator at NASA Ames Research Center.

CONCLUSIONS

This paper has presented the results of an experiment consistent with an explanation that attentional tunneling with HUD symbology is the result of differential motion between the symbology and the forward visual scene. Scene-linked symbology, the placement of enhancements, augmentations, or instruments virtually into the environment via HUD symbology was proposed as a design solution to alleviate attentional tunneling. An application of scene-linked symbology for low-visibility taxi was discussed.

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