Article

Glaucoma and Driving Risk under Simulated Fog Conditions

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Purpose: We evaluate driving risk under simulated fog conditions in glaucoma and healthy subjects.

Methods: This cross-sectional study included 41 glaucoma patients and 25 age-matched healthy subjects who underwent driving simulation. Tests consisted of curve negotiation without and with fog preview at 30 m of distance and two controlled speeds (slow and fast). Inverse time-to-line crossing (invTLC) was used as metric to quantify risk; higher invTLC values indicating higher risk, as less time is available to avoid drifting out of the road. Piecewise regression models were used to investigate the relationship between differences in invTLC in fog and nonfog conditions and visual field loss.

Results: Glaucoma patients had greater increase in driving risk under fog compared to controls, as indicated by invTLC differences (0.490 ± 0.578 s^{-1} and 0.208 ± 0.106 s^{-1}, respectively; $P = 0.002$). Mean deviation (MD) of the better eye was significantly associated with driving risk under fog, with a breakpoint of -9 dB identified by piecewise regression. For values below the breakpoint, each 1 dB lower MD of better eye was associated with 0.117 s^{-1} higher invTLC under fast speed (adjusted $R^2 = 57.9\%$; $P < 0.001$).

Conclusions: Glaucoma patients have a steeper increase in driving risk under fog conditions when compared to healthy subjects, especially when the severity of visual field damage falls below -9 dB of MD in the better eye.

Translational Relevance: By investigating the relationship between driving risk and disease severity breakpoint, this study may provide guidance to clinicians in recognizing glaucoma patients who may be unfit to drive in complex situations such as fog.

Introduction

Glaucoma is a progressive optic neuropathy characterized by degeneration of retinal ganglion cells and their axons. The disease frequently results in visual field loss and is one of the leading causes of visual impairment.[1,2]

Driving is the primary mode of transportation worldwide and the ability to drive is intimately associated with health-related quality of life.[3–5] As a visually intensive task, driving potentially could be affected by conditions, such as glaucoma.[6,7] Although glaucoma seems to be associated with higher risk for motor vehicle collisions (MVCs),[8–14] the specific driving conditions and disease characteristics that can lead to increased driving risk have not been well clarified.

Fog is one of the most dangerous conditions to drive in. Collisions in poor visibility conditions, such as fog, tend to result in more severe injuries and involve more vehicles.[15] Previous studies have suggested that drivers tend to underestimate their speed when driving in fog conditions and, thus, drive too fast for the available preview.[16–18] This occurs because a reduction in optic flow and scene contrast suppress perception of speed under these adverse conditions. Since fog causes a reduction in contrast of the visual field, the apparent speed of the vehicle slows, causing the individuals to drive faster.[16]

Due to safety concerns, studies of driving risk

under fog are difficult to perform using vehicles in a real environment. However, driving simulation has been used extensively to investigate driving risk under fog.[19–25] In one study, older drivers were found to be at greater risk for MVCs in dense fog due to a decreased ability to quickly detect impeding collision events.[23] Due to the loss of visual sensitivity, it is possible that glaucoma patients may have an even more pronounced increase of driving risk under fog compared to healthy subjects. However, to the best of our knowledge, this relationship has not been investigated previously in the literature.

The purpose of this study was to evaluate whether glaucoma patients experience a greater increase in risk when driving under fog conditions compared to age-matched healthy control subjects.

Methods

Participants from this study were included in a prospective longitudinal study designed to evaluate functional impairment in glaucoma conducted at the Visual Performance Laboratory of the University of California, San Diego. The institutional review board at the University of California, San Diego approved the methods, and written informed consent was obtained from all participants. The study adhered to the laws of the Health Insurance Portability and Accountability Act, and all study methods complied with the Declaration of Helsinki guidelines for human subject research.

All participants underwent a comprehensive ophthalmologic examination, including review of medical history, visual acuity, slit-lamp biomicroscopy, intra-ocular pressure measurement using Goldmann applanation tonometry, corneal pachymetry, gonioscopy, dilated funduscopy examination, stereoscopic optic disc photography, and standard automated perimetry (SAP) using the 24-2 Swedish Interactive Thresholding Algorithm (SITA) Standard of the Humphrey Field Analyzer II (Carl Zeiss Meditec, Inc., Dublin, CA). Only patients with reliable test results ($\leq$33% fixation losses and $\leq$15% false-positives) were included. Visual acuity was measured using the Early Treatment Diabetic Retinopathy Study chart and letter acuity was expressed as the logarithm of the minimum angle of resolution (logMAR). Only subjects with open angles on gonioscopy were included. Patients with coexisting retinal disease, cataract (Lens Opacities Classification System III grade $\geq$2),[26] uveitis, amblyopia, or nonglaucomatous optic disc neuropathy were excluded from the study.
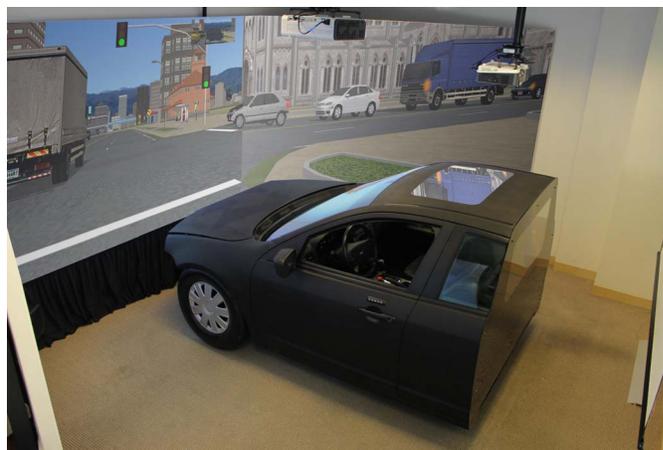
Figure 1. High-fidelity driving simulator (Realtime Technologies, Inc.) consisting of a B pillar forward full-size Ford Fusion cab equipped with a realistic motion platform, three 1920 $\times$ 1200 resolution projectors displaying the image on the front screens, two LCD displays used in the side mirror housings, a large flat screen/projector combination behind the cab, and a 5.1 sound system with full Doppler effect.

Glaucoma was defined by the presence of two or more consecutive abnormal SAP tests, defined as a pattern standard deviation with $P < 0.05$ and/or glaucoma hemifield test results outside normal limits, and evidence of glaucomatous optic neuropathy based on masked assessment of stereo photographs. A subject was considered to have glaucoma if damage was present in at least one eye. All subjects participating in the study were active drivers with a valid California driver license and completed the Montreal Cognitive Assessment (MoCA) test, a cognitive screening tool developed to detect mild cognitive impairment.[27]

Driving Simulator

All subjects drove in a high-fidelity driving simulator (Realtime Technologies, Inc., Royal Oak, MI) consisting of a B pillar forward full-size Ford Fusion cab equipped with a realistic motion platform, force feedback steering, and vacuum assist brake system (Fig. 1). A three-degrees of freedom motion-system allows the vehicle to pitch, roll, and heave to provide vestibular cues along with the visual scene. The visual system consists of three 1920 $\times$ 1200 resolution projectors displaying the image on the front screens for a total of 210°. Two LCD displays are used in the side mirror housings and a large flat screen/projector combination behind the cab allows the driver to use side and rear views. A 5.1 sound
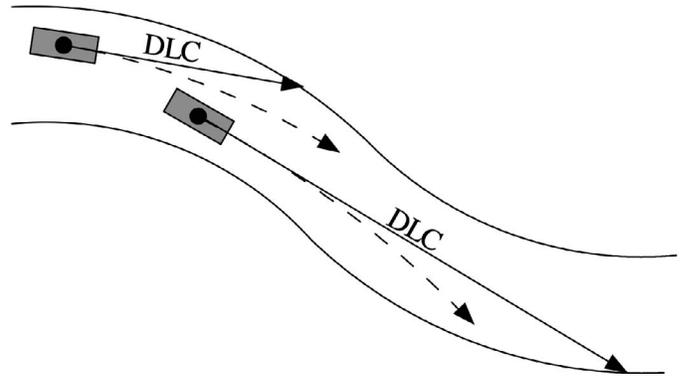
Figure 2. Curve negotiation task under fog condition. The task required drivers to drive on an ordinary winding road within a lane width of 3.6 m with a fog that limited preview to 30 m.

Figure 3. Distance to line crossing (DLC) is the distance between the center of the vehicle and the point at which the vehicle's heading vector intersects one of the two-lane edge. *Solid arrows* show the straight heading DLC and *dashed arrows* show the actual path if the current steering angle is maintained. TLC = DLC/speed.

system with full Doppler effect surrounds the vehicle for realistic vehicle and ambient traffic sounds.

The tests consisted of a curve negotiation task on a winding country road without and with fog (Fig. 2). The curve negotiation task required drivers to drive on an ordinary winding road within a lane width of 3.6 m for 2 minutes. After a practice session, the curve negotiation task was performed without fog. Subsequently, drivers were required to drive the same scenario, this time with a fog that limited preview to 30 m. The nonfog and fog drives were completed at two automatically controlled speeds of 35 (slow) and 55 (fast) miles per hour, which means that the drivers could not control their speed (accelerate or decelerate the vehicle) during the test. This allowed that both groups performed the tasks in the same scenarios and at the same speeds, assuring an equally demanding task for both groups, thereby eliminating the effect of individual differences that would be caused by speed choice.

The road curvature profile and the two speeds were chosen such that the driving task was more demanding at the fast speed.[28] By using a sum of sinusoids for the road curvature profile, continuous steering was

required (never a constant radius turn), and the participants would be less likely to recognize certain curve patterns that could cause them to steer also based on memory rather than solely on perception. Such a road that requires continuous visually-based vehicle control is expected to increase performance assessment sensitivity.

A preview time of approximately 2 seconds to the visibility limit of road marking ahead is considered an absolute minimum limit for safe driving.[29] The fog preview distance at 30 m at these particular speeds was chosen such that the slow speed fell on this 2-second limit while the high speed caused drivers to experience a high level of visual demand to protect their safety margins and, thus, their risk. These conditions allowed us to assess driving performance and risk under normal conditions and under simulated high-risk conditions caused by a short preview.

Driving performance was quantified using time-to-line crossing (TLC). Mathematically, it is defined as the distance between the center of the vehicle and the point at which the vehicle's heading vector intersects one of the two lane edges divided by the speed (Fig. 3).[30] It quantifies a safety margin measuring the time available to the driver before the car would leave the lane.[28,31] Time-to-line crossing has been shown to be a valuable method to quantify curve-driving performance.[30,32] On a straight road, TLC can become very large or even infinite. To avoid this numerical singularity in data analysis, the inverse TLC (invTLC) can be used.[33] Also, since drivers try to avoid risk by having a larger safety margin, invTLC transfers to a risk measure. Higher invTLC values indicate greater risk, as less time is available to avoid drifting out of

Table 1. Demographic and Clinical Characteristics of Subjects Included in the Study

	Glaucoma, $n = 41$	Control, $n = 25$	P Value
Age, y	69.0 ± 10.9	65.7 ± 9.9	0.220*
Sex, n (%) female	9 (22.0)	12 (48.0)	0.033†
Race, n (%)			
White	20 (48.8)	15 (60.0)	0.163†
African American	9 (21.9)	9 (36.0)	
Asian American	8 (19.5)	1 (4.0)	
Other	4 (9.8)	0 (0.0)	
MD of worse eye, dB	−12.8 ± 10.3	−0.7 ± 1.5	< 0.001‡
MD of better eye, dB	−6.5 ± 7.2	0.2 ± 1.2	< 0.001‡
Binocular MS, dB	24.2 ± 7.4	31.2 ± 1.7	< 0.001‡
Visual acuity of worse eye, logMAR	0.11 ± 0.23	−0.01 ± 0.14	0.004‡
Visual acuity of better eye, logMAR	0.02 ± 0.12	−0.07 ± 0.12	0.004*
MoCA score, units	28.0 ± 2.2	28.3 ± 2.5	0.415‡
Driving exposure, miles per wk	116.0 ± 107.5	117.6 ± 116.5	0.942‡

Values are presented as mean ± SD, unless otherwise noted. MS, mean sensitivity.
* Student t test.
† Fisher's exact test.
‡ Wilcoxon rank-sum test.

the road, and the driver, therefore, experiences smaller safety margins. For example, an invTLC of 0.5 s^{-1} indicates that the driver is about to drift out of the road within 2 seconds if the current heading were maintained or equivalently if the driver would let go of the steering wheel.[28]

Statistical Analysis

Univariable and multivariable regression models were used to investigate differences in driving risk between glaucoma patients and healthy control subjects under different fog and speed conditions, and also to investigate the effect of severity of visual field loss (SAP mean deviation [MD] of better eye) on driving risk. Piecewise regression models, in which the independent variable is partitioned into intervals and separate regression lines are fitted to each interval, also were used to determine whether a breakpoint in the MD of the better eye existed that could be interpreted as a critical value below which driving risk may begin to become significantly greater due to the inability to compensate for the visual loss. Multivariable models adjusted for potentially confounding variables, such as visual acuity, age, sex, race, cognitive impairment (MoCA score), and driving exposure (average mileage driven per week).

All statistical analyses were performed using commercially available software Stata, version 14

(StataCorp LP, College Station, TX). The α level (type I error) was set at 0.05.

Results

The study included 41 glaucoma patients and 25 healthy control subjects. Table 1 describes the demographic and clinical characteristics of included subjects. Average SAP MD of the worse and better eyes of glaucoma patients were −12.8 ± 10.3 dB and −6.5 ± 7.2 dB, respectively (Table 1).

Table 2 shows the results of driving risk as assessed by invTLC in glaucoma and control subjects under fog and nonfog conditions. In the nonfog clear condition, statistically significant differences were seen between glaucoma and healthy controls, with higher invTLC values for glaucoma patients at slow speed (0.349 ± 0.020 vs. 0.339 ± 0.012 s^{-1}, respectively; $P = 0.027$), as well as at fast speed (0.809 ± 0.171 vs. 0.723 ± 0.050 s^{-1}, respectively; $P = 0.004$). Under fog, driving risk also was greater in glaucoma patients at slow (0.373 ± 0.037 vs. 0.356 ± 0.013 s^{-1}, respectively; $P = 0.044$) and fast (1.299 ± 0.581 vs. 0.931 ± 0.097 s^{-1}, respectively; $P < 0.001$) speeds.

We were interested in determining whether glaucoma patients experienced a significantly greater increase in driving risk under simulated fog conditions

Table 2. Results of Driving Risk Metric (invTLC) in Glaucoma Patients and Healthy Control Subjects

invTLC	Glaucoma, $n = 41$	Control, $n = 25$	P Value*
Slow speed, 35 mph			
Nonfog, s^{-1}	0.349 ± 0.020	0.339 ± 0.012	0.027
Fog, s^{-1}	0.373 ± 0.037	0.356 ± 0.013	0.044
Difference, s^{-1}	0.024 ± 0.016	0.017 ± 0.016	0.583
Fast speed, 55 mph			
Nonfog, s^{-1}	0.809 ± 0.171	0.723 ± 0.050	0.004
Fog, s^{-1}	1.299 ± 0.581	0.931 ± 0.097	<0.001
Difference, s^{-1}	0.490 ± 0.578	0.208 ± 0.106	0.002

Values are presented as mean $\pm$ SD, unless otherwise noted. Difference is Fog minus Nonfog. mph, miles per hour.
* Wilcoxon rank-sum test.

compared to controls. Therefore, we calculated and compared the differences in invTLC between fog and nonfog for the two groups. When driving at fast speed under fog, glaucoma patients showed a significantly greater increase in risk compared to controls. The mean invTLC difference was 0.490 ± 0.578 s^{-1} for glaucoma subjects compared to 0.208 ± 0.106 s^{-1} for healthy controls ($P = 0.002$; Table 2). Such difference was not observed in slow speed.

A breakpoint of -9 dB that yielded the best fitting model in a piecewise regression was determined. In this model, for disease severity better than the breakpoint (MD of better eye higher than -9 dB), there was no significant relationship between increase in driving risk under fog and severity of visual field loss. However, the relationship between driving risk and disease severity became highly significant when considering MD values below or equal to the breakpoint, as indicated in Figure 4. When MD of the better eye was less than or equal to -9 dB, each 1 dB lower MD was associated with 0.004 s^{-1} higher invTLC difference in slow speed (adjusted $R^2 = 29.2\%$; $P = 0.016$) and 0.117 s^{-1} higher invTLC difference in fast speed (adjusted $R^2 = 57.9\%$; $P < 0.001$). In the multivariable model, when MD of the better eye was less than or equal to -9 dB, severity of visual field loss still was significantly associated with increase in driving risk. Each 1 dB lower MD of the better eye was associated with 0.105 s^{-1} higher invTLC difference in fast speed ($P < 0.001$; Table 3).

Table 3. Results of the Piecewise Univariable and Multivariable Regression Models for Explaining Relationship Between Differences in Driving Risk Metric (invTLC) under Fog and Nonfog Conditions in Fast Speed and Severity of Visual Field Loss (MD of Better Eye)* in Glaucoma Patients and Healthy Control Subjects

	Univariable Model		Multivariable Model	
Characteristic	Coefficient (95% CI)	P Value	Coefficient (95% CI)	P Value
MD of better eye, ≤-9 dB*, per 1 dB lower	0.117 (0.075–0.159)	< 0.001	0.105 (0.058–0.153)	< 0.001
MD of better eye, >-9 dB*, per 1 dB lower	−0.011 (−0.045–0.024)	0.536	−0.005 (−0.046–0.037)	0.827
Visual acuity of better eye, per 0.1 logMAR higher	0.144 (0.055–0.232)	0.002	0.036 (−0.045–0.118)	0.375
Age, per decade older	0.056 (−0.056–0.167)	0.325	0.030 (−0.054–0.114)	0.475
Sex, female	0.090 (−0.164–0.343)	0.483	0.027 (−0.157–0.212)	0.766
Race, African American	0.242 (−0.017–0.502)	0.066	0.147 (−0.062–0.356)	0.165
MoCA score, per 1 unit lower	0.009 (−0.042–0.061)	0.721	−0.006 (−0.044–0.032)	0.747
Driving exposure, per 100 miles per wk lower	0.115 (0.011–0.220)	0.031	0.024 (−0.059–0.106)	0.569

CI, confidence interval.
* Mean deviation of better eye was partitioned into two intervals ($\leq$ and >-9 dB) in a piecewise regression.
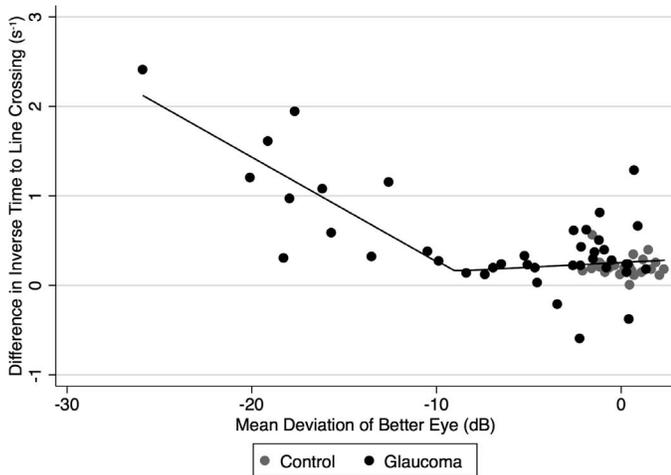
Figure 4. Scatterplot with piecewise fitted regression line illustrating the relationship between difference in invTLC (s^{-1}; fog minus nonfog conditions) and MD of better eye (dB) at fast speed.

Discussion

The presence of fog reduces visibility, optic flow, and effective field of view, making for a challenging driving experience. However, even though some degradation of driving performance under fog can be expected for most drivers, our results showed that glaucoma patients had a steeper increase in driving risk under fog compared to healthy control subjects.

In a curve negotiation task, the driver must match the road curvature and keep a proper distance from the lane edges. In our study, we found that the presence of fog significantly reduced the time to drift out of the road for glaucoma patients compared to healthy controls, as indicated by the invTLC metric. This finding indicates that glaucoma patients had a lower safety margin and could be at higher risk for MVCs when driving under fog. We showed that severity of visual field loss as assessed by SAP was significantly associated with greater increase in driving risk under fog conditions at slow and fast speeds. Interestingly, a breakpoint was identified in the relationship between driving risk and disease severity. For patients with disease severity (SAP MD in the better eye) above the breakpoint of −9 dB, no statistically significant relationship was seen between disease severity and driving risk. In contrast, a steep relationship was seen for those with disease severity below the breakpoint. These findings seem to suggest the possibility that, up to disease severity levels of −9 dB in the better eye, the visual system still seems to be able to compensate and provide adequate input for successful task performance, avoiding excessive risk. However, below the breakpoint, there seems to be a quick "breakdown" leading to rapid degradation in performance and increase in risk. It should be noted, however, that the value of −9 dB obtained in our study was specific to the tasks and population studied and may differ in other situations.

In fog, visibility (i.e., contrast) is reduced with increasing distance. Therefore, when the driver looks straight ahead, the regions of better visibility are located near the vehicle and are viewed with the peripheral field, whereas the regions of worse visibility are located far from the vehicle and are viewed with the central field.[34] When negotiating a curve, the far region is needed to detect which direction the road is going so that anticipatory steering can be employed, whereas the near region (peripheral) is needed to detect large lateral deviations and drifts so that corrective steering can be applied. An increase in driving risk under fog would be expected for healthy and glaucoma subjects due to the difficulty in performing anticipatory steering from the reduced vision at far distance caused by the fog. This was, in fact, shown in our study, as glaucoma and healthy subjects had greater risk in fog compared to nonfog situations. In addition, patients with glaucoma and significant visual field loss also would have greater difficulty in performing corrective steering measures, as these are mostly dependent on the peripheral vision. This likely explains the significant increase in driving risk under fog for glaucoma patients compared to healthy subjects, as shown by reduced times to drift out of the lane. It is important to note that even though differences in driving risk between glaucoma and healthy subjects also were seen in nonfog conditions, these differences were much smaller in nonfog than in fog. That is, when challenged by fog, glaucoma patients with substantial visual field loss had a steeper increase in driving risk compared to healthy subjects.

Our results showed that the effect of fog was worse under faster speeds. This is expected, as driving in fast speed will be more demanding, especially under fog. Although drivers know they should slow down because fog reduces visibility, many still will drive too quickly. Previous studies have suggested that drivers tend to underestimate their speed when driving under fog conditions.[16–18] In foggy conditions, drivers may think they are driving more slowly than they actually are and, therefore, increase their speed. Due to their reduced field of view, speed

misestimation could be even worse for glaucoma patients. In our study, we used fixed speeds for the driving tasks to avoid confounding effects of different speeds that could be adopted by patients. In the present study, we used a controlled driving speed to decrease its confounding effect in the study of the association between fog and driving risk. However, future investigations should evaluate the effect of speed estimation on driving risk in glaucoma.

Evidence suggests that glaucoma patients seem more likely to avoid high-risk driving situations.[35] Ono et al.[36] showed that, among 252 glaucoma subjects, 18% avoided driving in fog. However, in a recent study (Correa PC, et al. IOVS 2016:57:ARVO E-Abstract 3420), we showed that there is only a relatively weak relationship between subjective concerns about driving ability and objective driving performance in patients with glaucoma. Only approximately one-third of patients who were identified as having unsatisfactory driving performance on a simulator actually had significant concerns about their ability to drive, suggesting that a large number of patients with glaucoma may not adopt necessary precautions to avoid risky driving situations. By investigating the relationship between driving risk and disease severity breakpoint, our study may provide guidance to clinicians in recognizing glaucoma patients who may be unfit to drive in complex situations, such as fog. Our results also suggested that individualized assessment of driving fitness using driving simulators could be helpful in providing further assessment of driving risk.[38–40]

The present study had limitations. Even though driving simulator metrics have been shown to be predictive of real-life driving metrics, it is possible that our estimates of risk may differ from those that would occur in real-life situations. However, exposing subjects to the risky situations simulated in our study would be difficult, if not impossible, in real life. In addition, behind-the-wheel investigations would not allow controlled experimental conditions, such as exposing the patients to the same amount of fog under the same road and speed conditions. As another limitation of our study, the relatively small sample did not allow us to investigate the relationship between patterns and locations of visual field defects and their impact on driving risk. Future studies should investigate whether specific patterns of defects may affect driving risk.

In conclusion, patients with glaucoma had a significantly greater increase in driving risk when challenged by simulated fog conditions compared to healthy control subjects. Driving risk under fog showed a tight relationship with disease severity for patients with SAP MD in the better eye lower than −9 dB, suggesting a breakpoint below which the visual system seems unable to adequately compensate for the demands of driving in this situation. Therefore, subjects with visual field damage that falls below this breakpoint may be at increased risk when performing complex driving tasks.

Acknowledgments

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