64Modeling Operator Performance Considering Autonomy Level in Partially Autonomous Vehicles

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ABSTRACT

To fully utilize the abilities of current autonomous vehicles, it is necessary to understand the interactions between the vehicles and their operators. Since the current state of the art of autonomous vehicles is partial autonomy that requires operators to perform parts of the driving task and to be alert and ready to take over full control of the vehicle, it is necessary to know how the operators' abilities are impacted by the amount of autonomy present in the system. Autonomous systems have known effects on performance, cognitive load, and situation awareness, but little is known about how these effects change in relation to distinct, increasing autonomy levels. It is also necessary to consider these abilities with the addition of secondary tasks due to the appeal of using autonomous systems for multitasking.

The goal of this research is to use a web-based virtual reality study to model operator situation awareness, cognitive load, driving performance, and secondary task performance as a function of five distinct, increasing levels of partial vehicle autonomy with a steadily increasing rate of secondary tasks. The study had each participant operate a virtual military vehicle in one of five possible autonomy conditions while responding to questions on a communications terminal. Participants took part in an experimental drive where they would have to intervene to prevent crashes regardless of autonomy level.

The factors of scored driving performance, secondary task performance, subjective situation awareness, and cognitive load, were analyzed in terms of how they related to the autonomy level and to each other. Results are presented in the form of statistical analysis and modeled equations and show the potential for optimal multitasking within specific autonomy levels and task allocation requirements.

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INTRODUCTION

The current state of the art in autonomous vehicles is partial autonomy. Such systems require the operator to monitor the driving task to be ready to intervene at any point. To create optimal systems using these systems, it is necessary to develop an understanding of the interaction of the human operator with the partially autonomous vehicle.

Previous findings could lead one to expect increasing levels of vehicle autonomy to have a negative impact on situation awareness and cognitive load (Johns et al., 2014) (Endsley, 2019) (Lisanne Bainbridge, 1983), but there are many factors that make this relationship complicated and warranting of a full investigation. Among these are the desire to use autonomy to allow for multitasking as well as the need to find balance between underload and overload regarding operator cognitive taskload (Lisanne Bainbridge, 1983).

The overall motivation of this research is to create a system of dynamic allocation to reduce the number of crew members needed on military missions through the use of partially autonomous vehicles (Cossitt, Hudson, et al., 2020). The information gained in this experiment builds upon a previous experiment looking at operator abilities with a constant rate of secondary tasks (Cossitt, Patel, et al., 2022) by adding a steadily increasing rate of secondary tasks. The data from both experiments is used to model operator ability at many distinct levels of partially autonomous vehicle operation while taking into account the use of autonomy to allow for operator multitasking. Such a model could be used to develop better autonomous systems designed with the operator in mind. Ideally, systems would be able to predict operator behavior and take measures to increase engagement in scenarios where situation awareness is known to decrease. Additionally, this model creates a better understanding of what should be required of the autonomous system in situations where operator takeover is necessary.

The data attained from this study was statistically analyzed and used to create a mathematical model to determine the best way to optimize for performance in both driving and secondary tasks in each autonomous driving scenario. This created model is used to make recommendations for the design of future interfaces for autonomous vehicle systems.

RELATED WORK

Previous work has established the desire to use autonomous vehicle technology to reduce the number of crew members needed on missions (Anderson et al., 2018). This goal of this work was to reduce a three-person crew to a two-person crew. It proposed static allocation methods that depended on communication and task sharing between the two crew members.

Various military studies have investigated multiple aspects of mission task optimization. A study focusing specifically on tasks other than vehicle operation by Metcalfe et al. (2010) evaluated situation awareness and cognitive load of soldiers. This research found that when detecting threats soldiers could easily become overloaded with too many tasks and limited by short term memory. A study by Hollands et al. (2019) also evaluated situation awareness and cognitive load when receiving commands. This study found that situation awareness and cognitive load were less negatively

impacted by auditory commands than by visual commands as well as less negatively impacted by a fast rate of commands than by a slow rate of commands.

Additional research of interest has been done with normal civilian driving conditions examining handover situations in partially autonomous vehicles (Miller et al., 2014). This study looked at the effects of different autonomous vehicle abilities on operator performance. The results showed that some autonomous vehicle abilities have more profound effects on operator performance than others.

EXPERIMENT DESIGN

A total of 180 participants were recruited for this study using Amazon Mechanical Turk. These participants also completed a previous phase of research prior to this experiment (Cossitt, Patel, et al., 2022) and were familiar with the operation of the vehicle. Participants were each assigned to one of five possible conditions of vehicle autonomy (the same condition they had previously been assigned for the prior experiment) where they performed the task of supervising and operating the vehicle as well as performing secondary tasks over the course of an eleven-minute drive. The data from 30 participants was unusable due to the participants failing to complete the entire experiment. This resulted in 150 usable data points, 30 from each autonomy condition.

The five autonomy conditions (shown in Table 1) each built upon the autonomous abilities of the previous condition. Condition one had no autonomous vehicle abilities. Condition two added longitudinal control or adaptive cruise. Condition three added lateral control or lane keeping. Condition four added automated turning at intersections. Finally, condition five added detection and avoidance of stationary obstacles. None of the autonomy conditions could account for sudden events like an object suddenly entering the roadway directly in front of the vehicle. All participants were told they were responsible for intervening in case of such an emergency.

Table 1. Autonomy Conditions

Autonomy Condition	Vehicle Abilities
1	No Autonomy
2	Longitudinal Control (Adaptive Cruise)
3	Condition 2 + Lateral Control (Lane Keeping)
4	Condition 3 + Automated Turning at Intersections
5	Condition 4 + Obstacle Detection and Avoidance

Virtual Environment

The vehicle was simulated using a web based virtual reality approach developed using Unreal Engine 4 (Unreal Engine Documentation, 2019). Participants accessed the experiment website and operated the vehicle using keyboard controls on their own computers. The environment (shown in Figure 1) consisted of the interior of a closed-hatch military vehicle. Directly in the center of the participants' view was a steering wheel and dashboard as well as an indirect view screen showing the view of the road and outside world. To the right of the indirect view screen was a communications console where participants responded to yes or no questions about the environment and the vehicle gauges as a secondary task. To control the movement of the vehicle, participants could choose to use either the arrow keys or the 'W', 'A', 'S', and 'D' keys as these are commonly used video game controls. To respond to the communications

console tasks, participants clicked on the prompt below the question, typed their response, and then either pressed the enter key or clicked away from the prompt.

Figure 1. View of the Virtual Environment

Participants were told they were performing a surveillance task in an evacuated city. Barricades on the roads were positioned such that there was only one possible way to navigate through the environment. During the drive participants encountered three sudden road events that required intervention in order to avoid a collision. These events occurred at approximately three minutes, six minutes, and nine minutes into the drive. Each of the possible road events could only occur once and was selected at random from six possible events. These possible events included a pedestrian running into the road, a dog running into the road, a military truck pulling out into the road in front of the vehicle, a barrel rolling into the road, a ladder falling off a building into the road, and a box of rubbish falling off of a truck in front of the vehicle. An example of one of these road events can be seen in Figure 2.

Figure 2. A Sudden Road Event Where a Truck Pulls Out in Front of the Vehicle

Secondary Tasks

The new factor introduced in this experiment was an increasing rate of secondary task assignment. As opposed to the previous experiment where participants received two command console prompts per minute, in this experiment participants received command console prompts at a rate that steadily increased to a point that was intended to be unmanageable before slowing back down for a cool down period at the end of the drive. At the start of the drive participants received commands at a rate of two questions per minute. This then sped up over the course of the drive

to three questions per minute, four questions per minute, six questions per minute, twelve questions per minute, and twenty questions per minute before slowing back down to four questions per minute for the last minute of the drive. Table 2 shows a detail of the secondary task timings.

Table 2. Secondary Task Rate Changes

Time From Experiment Start	Task Rate (Tasks Per Minute)
0:00	2
1:20	3
2:15	4
5:10	6
7:55	12
8:43	20
9:25	4

EVALUATION

The evaluated factors of driving performance, secondary task performance, subjective situation awareness, objective situation awareness, and cognitive load in this study were measured in the same way as the previous experiment with constant task rate (Cossitt, Patel, et al., 2022). Driving performance, secondary task performance, and objective situation awareness were evaluated based on information collected during the drive. Subjective situation awareness, and cognitive load were evaluated based on surveys given after the drive.

To evaluate driving performance, an overall hazardous driving score was assigned based on the performance in multiple recorded aspects of the driving task. In addition to the overall score, the number of road events that resulted in collision was evaluated independently as a non-parametric factor. The performance areas evaluated for the overall hazardous driving score included the following:
- Number of sudden road events hit
- Number of other vehicles hit
- Number of barricades hit
- Number of stationary obstacles hit
- Number of forced autonomy control swaps

Performance on secondary tasks was evaluated by the percentage of accurate responses given, the average latency of the responses given, and an overall secondary task performance score that was calculated based on both accuracy and latency. This score was calculated with each accurate response being worth a maximum of thirty points if answered within five seconds of the question being asked. For each five seconds after that the points reduced by five with the minimum possible score for a correct response being one point.

Objective situation awareness was evaluated with real-time situation awareness prompts built into the communications console task. These prompts were based on the methodologies of the Situation Awareness Global Assessment Technique (SAGAT) (M. Endsley et al., 1998). The SAGAT recommends giving prompts during a pause of the situation, but Jones and Endsley (2000) validated the use of SAGAT prompts in real time when a pause is not an option. The prompts were also given visually rather than verbally as the SAGAT recommends because it was assumed that the prompts should not add task load of their own since they were built into task that was already being completed.

Subjective situation awareness was evaluated using the Situation Awareness Rating Technique (SART) (Taylor, 2017). The SART was given and evaluated according to the original documentation as a post-experiment survey where participants subjectively rated their situation awareness on a seven-point scale in ten categories.

Cognitive load was evaluated with two subjective post-drive surveys, the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988) and an adaptation of the SOS Scale (Swaak & De Jong, 2001). The NASA-TLX included six questions where participants subjectively rated their workload on a twenty-one-point scale. The SOS Scale which was adapted from its original use in evaluating learning technologies, was made up of four questions where participants responded on a scale from zero (very easy) to 100 (very difficult). The following are the adapted questions that were used:

- "I consider the task of operating the vehicle at this moment to be:"
- "I consider the task of responding to the communications tasks at this moment to be:"
- "Working with the system is for me at the moment:"
- "Use of the vehicle's technology make the overall task:"

In addition to these evaluation methods, evaluation was done on the effect of task rate across both this experiment and the previous one. Specifically, the relationship between task rate and response latency was examined as was the relationship between task rate and response accuracy.

RESULTS

A multivariate analysis of variance (MANOVA) was done to analyze global effects on the factors of hazardous driving score, secondary task score, real-time situation awareness score, SART score, NASA-TLX score, and SOS score. The MANOVA showed significant results $(F_{(4,145)} = 1.84, p= 0.009, \alpha= .05)$ with a medium effect size $(\eta^2_p = 0.07)$.

Univariate ANOVA's were done to determine contributing factors and showed significant results for hazardous driving score $(F_{(4,145)} = 4.213, p= 0.003, \alpha = .05)$ with a medium effect size $(\eta^2_p = 0.1)$ and for SART $(F_{(4,145)} = 2.87, p= 0.025, \alpha = .05)$ with a medium effect size $(\eta^2_p = 0.07)$.

Post hoc testing was done for both of these factors using Tukey HSD (Haynes, 2013-a). For hazardous driving score, significant differences for pairwise comparisons were shown between conditions two and one and conditions two and five. For SART, significant differences for pairwise comparisons were shown for conditions one and four and conditions two and four. Figure 3 shows the distribution for hazardous driving score for each condition, and Figure 4 shows the distribution for SART for each condition.

A Kruskal-Wallis rank sum test (The Concise Encyclopedia of Statistics. Springer, 2008) was done as a non-parametric test for the number of sudden road events resulting in collision during the drive. This test showed significant results with a p-value of 2.888e-08 and a chi-squared value of 40.85 with a large effect size $(\eta^2[H]=0.25)$. Figure 5 shows
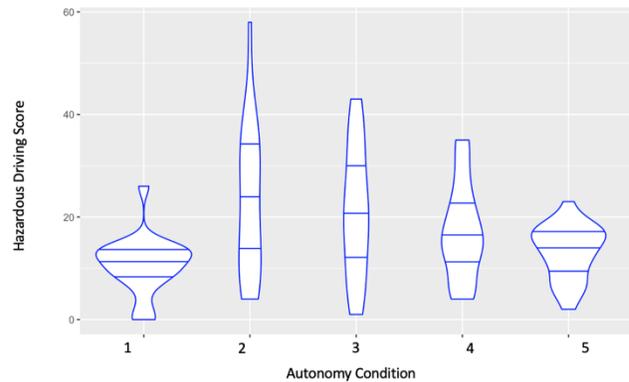

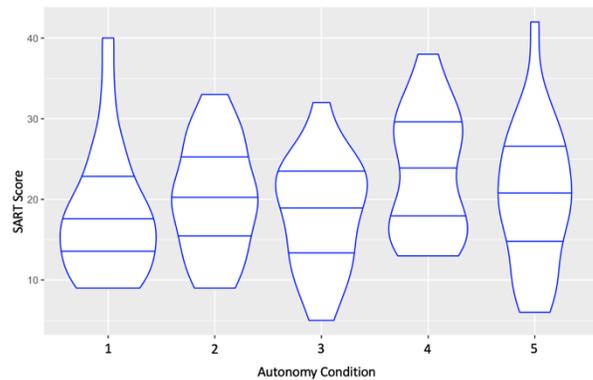**Figure 3. Violin Plots of Hazardous Driving Score**

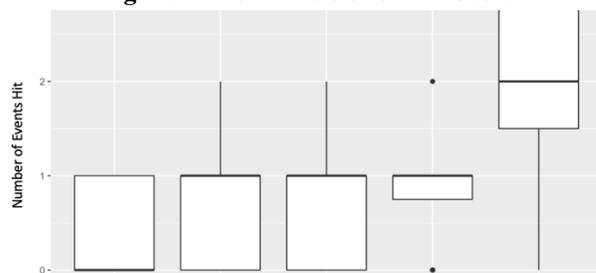**Figure 4. Violin Plots of SART Score**

Figure 5. Box Plots of Events Hit

a box plot of the distributions of events resulting in resulting in collision. A Wilcoxon rank sum test (Haynes, 2013.-b) was used as a post hoc analysis and showed that all significant pairwise comparisons were those involving condition five.

Exploratory analysis of the effects of task rate on task performance showed an interesting relationship among task rate, autonomy condition, and response latency. This relationship is depicted in the graph in Figure 6. This relationship is particularly interesting in the differences it shows among autonomy conditions. Conditions three and five, the middle and highest autonomy levels, show the worst performance with conditions one, two, and four being comparable after what appears to be a learning curve for condition four.

The graph shows the average latency for each question in each autonomy condition that was asked across both this experiment and the previous one. It is clear that there are distinct differences in the relationship of rate and latency at each autonomy level. Further analysis of these relationships was done using linear regression modeling at each task rate. The models produced in this analysis are shown in Figure 7.
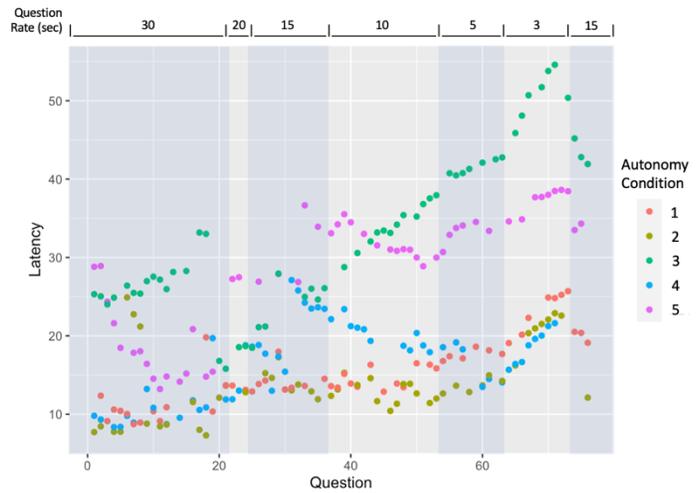

Figure 6. Latency of Task Response to Questions at Each Rate and Each Autonomy Condition
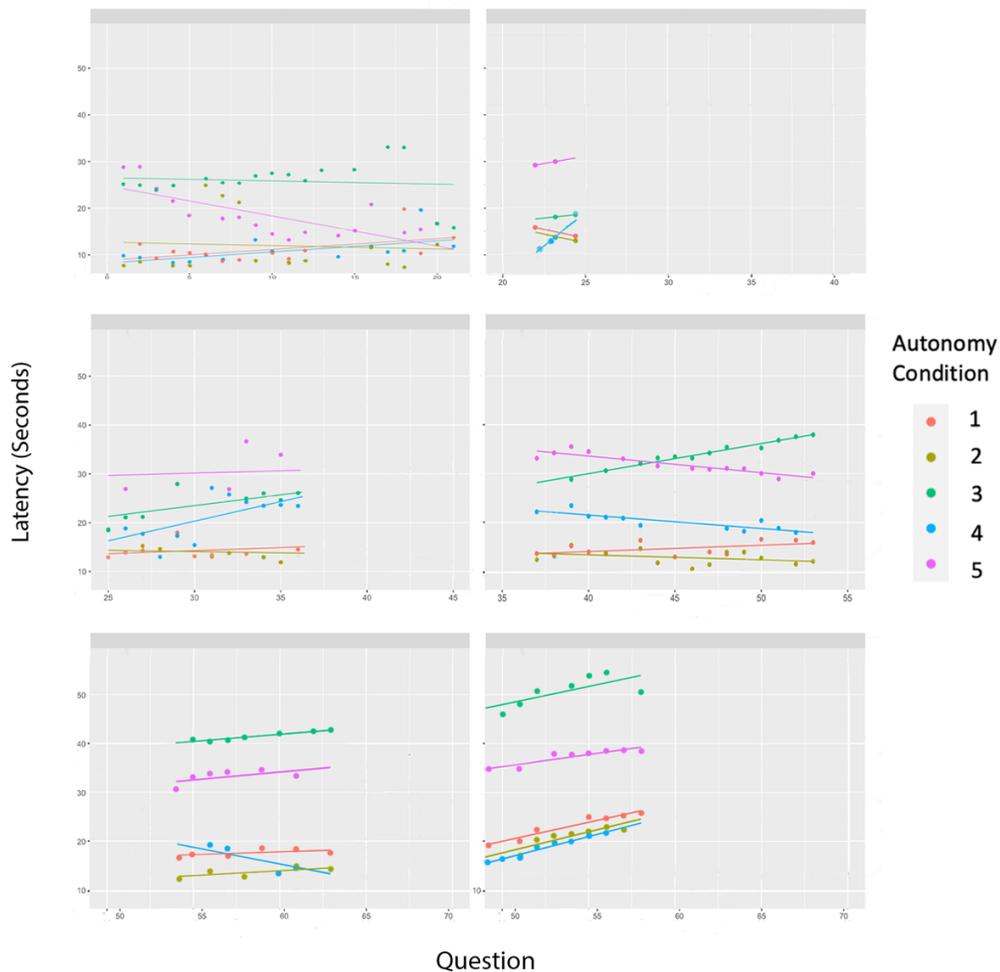
Figure 7. Multiple Linear Regression Models for Latency and Condition at Each Rate

Statistical validation these models showed overall interactive statistical significance for the models with rates of two questions per minute ($F(9,67)=19.67$, $p=1.246e-15$), four questions per minute ($F(4,40)=51.52$, $p=2.2e-16$), six questions per minute ($F(9,51)=509.7$, $p=2.2e-16$), twelve questions per minute ($F(9,21)=578.2$, $p=2.2e-16$, and twenty questions per minute ($F(9,27)=416.9$, $p=2.2e-16$). Statistical significance was not found on the model of the twenty second interval which had very few data points. All the significant results showed large effect sizes using R squared for multiple regression. These included the models for rates of two questions per minute ($R^2 = 0.72$), four questions per minute ($R^2 = 0.92$), six questions per minute ($R^2 = 0.99$), twelve questions per minute ($R^2 = 0.996$), and twenty questions per minute ($R^2 = 0.99$).

These results show that there is a predictable rate of change in latency for each condition at each rate. Additionally, a significant effect was not found for response accuracy which implies that if latency can be controlled for based on these predictable relationships, operator performance can be optimized.

Figure 8 Shows an overall model of all the results found across both this study and the previous experiment.
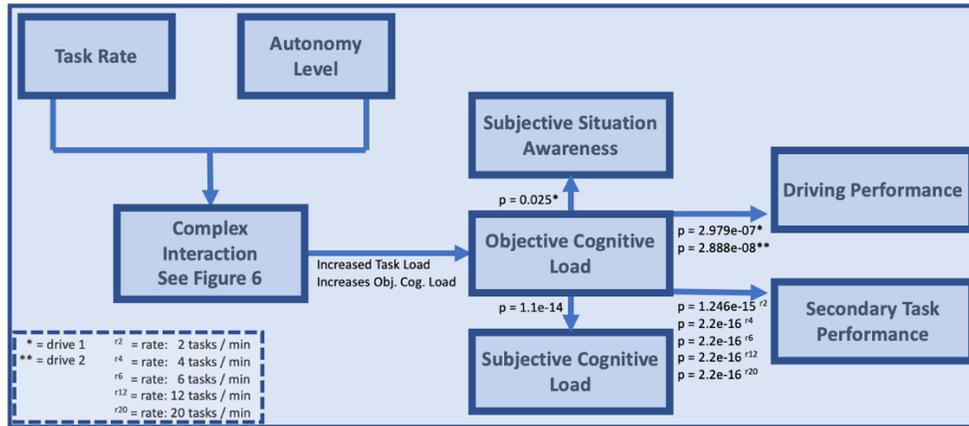
Figure 8. Visual Model of Found Interactions

DISCUSSION

The significant result showing that driving performance is affected by autonomy level is consistent with the results of the previous study (Cossitt, Patel, et al., 2022) including the interesting aspect of all significant differences for sudden events resulting in collision involving the highest autonomy condition. This indicates that in partially autonomous vehicles where the operator is in a supervisory role, only taking over the driving task in the case of emergencies, they are much less capable of responding to such problems than when they the task with the system. This shows that is crucial for vehicles to draw the operator's attention back to the driving task periodically. In this study, operators in the second highest autonomy condition where they were occasionally required to take control to navigate around an obstacle were capable of noticing and avoiding sudden events as well as any other condition. This indicates that requiring a supervisory operator to occasionally take over the driving task, even for very brief periods, can increase their engagement to the highest observed level.

Unlike the previous experiment, with increased task load, this study showed significant results for SART. Additionally, these results showed that subjective situation awareness was the most optimal in condition four, the second highest autonomy condition which only required occasional takeover.

There was a strong interactive relationship found in this study among secondary task rate, secondary task latency, and autonomy level. Because a major appeal to the use of autonomous vehicles is their potential to allow for higher degrees of multitasking, especially in a military context, this result can inform what rate of secondary task assignment is possible at each distinct level of partial autonomy. Based on the models shown in Figure 7, it is possible to make recommendations for secondary task assignment based on the levels of partial autonomy used in this study. Table 3 shows these recommendations.

Table 3. Recommended Rates of Secondary Task Assignment

Level of Partial Autonomy	Rate Where Tasks Can Be Added (Tasks per Minute)	Rate Where Tasks Can Be Performed Stably (Tasks per Minute)	Rate Where Tasks Can Be Performed for Brief Periods (Tasks per Minute)
1	3	4	20
2	3	4	20
3	2	3	20
4	3	4	20

5	2	3	20

For these recommendations, tasks are considered not to be performed stably when the rate of change in latency is greater than an increase of 0.5 seconds per task and the average latency is greater than or equal to the rate at which the tasks are being given without alternate explanation from examining the overall patterns of the data. Participants are considered to be able to perform tasks at a rate for brief periods when the overall latency is higher than the rate the tasks are being given but still correctly performed. In all conditions in this experiment, participants were capable of performing tasks correctly for brief periods at the highest tested rate of twenty tasks per minute, though their latency was dramatically impacted. For the above recommendations, it is assumed that the increased latency observed briefly in the highest autonomy levels starting when the intensity of tasks began to increase would be flattened to a more normal increase with more training.

Across both experiments, one autonomy condition, condition four, seemed to have optimal or equal-to-optimal results for all for the measured factors. In condition four, autonomy was capable of adaptive cruise, lane keeping, and automated turning at intersections, but it was not capable of detection and avoidance of stationary obstacles. The results seem to show that this amount of autonomy allowed operators to multitask but also required takeover for enough of the driving task to cause participants to remain engaged. In these experiments there was roughly one obstacle to be avoided per minute. This resulted in a necessary hand off (either forced by the autonomy or initiated by the operator) each time such an obstacle was encountered. This implies that forcing an operator's attention to the road at a regular interval could perhaps be a solution to the problem of attention loss in partially autonomous vehicles.

CONCLUSIONS

Significant results found in this study include the inability of operators to respond to sudden emergency events in purely supervisory roles in partially autonomous vehicles as well as findings indicating a complex relationship with autonomy level and operators' ability to perform secondary tasks. Results also tend to point to there being an optimal level of partial autonomy for the best performance on both primary and secondary tasks.

Based on knowledge acquired in this study it is possible to recommend how secondary task allocation should differ relative to vehicle autonomy. These rate recommendations are a new contribution to the field autonomous vehicle research and are of particular interest to military applications where autonomy is used to increase multitasking ability.

Additionally, the finding of the effect of autonomy level on driver performance shows that these effects only happen past a certain point of vehicle autonomy. This new contribution informs future decisions in partially autonomous vehicle design by showing at exactly what point performance begins to degrade in steadily increasing levels of autonomy. This could lead to better solutions designed with the user in mind.

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