Employing serious games to increase safety in driving through road tunnels

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Research has shown that tunnel safety is a matter of great importance. Recent studies have shown that, while driver behavior is one of the decisive factors in road tunnel accidents, drivers hardly receive proper education about the particularities of the tunnel environment, and they also exhibit deficiencies on how to deal with emergency situations inside a tunnel. As a means of tackling this challenge, the present research endeavor develops a software tool based on the concept of serious games, to educate and inform potential users on the specific rules and behavioral patterns that should govern driving through tunnels. To do so, the initial step was the determination of the basic instructions that a user must be familiar with, while driving through tunnels. The proper behavioral patterns were gathered from the relevant standards and guidelines and the specific needs for education have been explored through previous studies. Subsequently, the research proceeded with the development of an innovative tool for the purpose of users' training, consisting of a game environment which simulates from a first-person perspective the task of driving through a tunnel. Within this environment various different scenarios were developed with the aim of evaluating the knowledge of users as well as educating them. The ultimate aim is to further increase safety within road tunnels, focusing on driver behavior as one of the most crucial parameters.

Keywords: Road Tunnels, Road safety, Serious games, Simulation environment, Driver behavior, Behavioral patterns.

1. Introduction

Despite the significant advances regarding road safety in recent years, road accidents continue to be the cause of a considerably high number of deaths and injuries. In particular, driver error has been indicated as the main causal factor of road accidents due to its contribution in over 90 percent of accidents globally (WHO, 2020). In order to increase the level of road safety, drivers' behavior should be at the forefront. Initially, drivers' behavior has to be extensively analyzed and subsequently special emphasis should be given on the influence of education on drivers' behavior and attitude.

Taking into account the role of road infrastructure in the transportation of people and goods, infrastructure safety has become a significant factor in order to guarantee a high level of safety to the public. Because tunnels are considered a key element of the road infrastructure, their role is important in order to reach this goal (PIARC, 2016). Road tunnels constitute important infrastructure elements as their use improves transportation flow within urban areas and enables crossing mountains in rural areas. Moreover, they minimize the environmental impact as well as the time and the transportation costs. The use of tunnels has been boosted significantly because of the rapid improvement of underground technology that has rendered tunnels as a cost-effective engineering solution in developing new road networks. As a consequence, their numbers are increasing as more and more tunnels are developing worldwide (Ntzeremes & Kirytopoulos, 2019). However, the enclosed environment of tunnels bears a significant problem, which is the magnitude of the consequences from potential accidents in them. This issue was highlighted in the disastrous accidents occurred in the past (Ntzeremes & Kirytopoulos, 2018).

As far as the role of drivers' behavior in tunnels is concerned, recent studies have shown that drivers hardly receive proper education about the particularities of the tunnel environment while they exhibit serious deficiencies on how to deal with emergency situations inside a road tunnel (Kirytopoulos et al., 2017; Zeeri et al., 2019). In some countries, accident rates in tunnels appear to be lower in contrast to the rest of the road network while, in general,

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tunnel disasters are even scarcer (Ntzeremes & Kirytopoulos, 2019). However, taking into account that the number of tunnels continues to grow, the aforementioned results do not allow any complacency.

Therefore, the present research endeavor aims at enhancing the level of safety of road tunnels by employing serious games in order to increase safety in driving through road tunnels. To do so, a software tool based on the concept of serious games is developed in order to educate and inform potential users on the specific rules and behavioral patterns that should govern driving through tunnels. The reasoning behind the adoption of a serious game-based approach for the development of the above tool was two-fold. Firstly, since tunnel driving, like all driving, is first and foremost a practical/physical task and not a cognition-heavy one, it was deemed logical to develop an interactive rather than demonstrative tool to familiarize users with the desired instructions. Following that line of thought, the environment was designed to resemble those used in driving simulators, which are widely used in driver training worldwide, albeit in a more focused perspective, namely, tunnel driving. Secondly, training via serious games is nowadays explored in many fields as there is an expectation that it can actively increase knowledge acquisition and retention, as compared to traditional forms of education. In combination with the above similarity to driving simulators, it was the intent of the research team to utilize this effect in order to produce the best possible educational results.

The paper is organized as follows: After the short introduction a literature review is provided. Then in section 3 the methodology used to develop the serious game tool is described. The developed tool is presented in details in section 4 while section 5 concludes the paper.

2. Literature review

2.1. Drivers' Knowledge in Greece

Driving error is the main contributory factor of road accidents and its causes and consequences are of great interest in the road safety decision making processes (Elison, 2015; Tselentis et al., 2021). As far as road tunnels are concerned, a limited number of studies has explored the drivers' behavior and their level of knowledge on tunnel safety issues.

Kirytopoulos et al. (2017) study showed that drivers suffer from numerous misconceptions regarding driving through tunnels both in simple drive-through and critical situations. The outcome of this online questionnaire survey conducted in Greece indicated that drivers lack important pieces of knowledge for both normal and critical situations. Initially, tunnel drivers seemed to fail to spot the differences between driving in tunnels and driving in the open road sections. A considerable number of respondents admitted that often they do not keep the required distances in tunnels or may not confront to control signals and continue their route in their effort and will to reach their destination as fast as possible. Especially in cases of fire, respondents suggested that they would attempt U-turns, drive in reverse gear or try to overtake burning vehicles, although such behaviors are strictly discouraged. On the other hand, it should be noted that the respondents who claimed that they had received some information were more aware in questions relevant to reversing, U-turns and lane-closed signals.

Zeeri et al. (2019) survey indicates that, while participants believe that they adopt safer driving behavior than other users, and while they believe that they drive more carefully inside road tunnels than they do on the open road, almost none adheres to speed limits nor maintain the appropriate safety distance from the vehicles ahead. Furthermore, risk perceptions were also examined. The respondents believe that inside road tunnels they have better driving control, an accident is more possible to occur and the consequences of any accident would be more severe than on an open road section. Moreover, participants perceive their personal vulnerability towards risk to be less than the general population's, something that is a well-known phenomenon in safety studies (control effect). This optimistic perception is associated with the level of road tunnel emergency training. Finally, the outcome illustrates that some of the respondents are neither familiar with the use of fire extinguishers and emergency telephone booths nor willing to leave their vehicle behind in case of an accident.

Kirytopoulos et al. (2020) compared the answers of the participants about themselves with their answers about the other drivers around them. The differences between how drivers evaluated themselves and how they evaluated the other drivers may illustrate an unbiased picture of driving habits and potential behavioral intentions. Indeed, it was found that, participants believe that they adopt safer driving behavior than other drivers, and they believe that they drive more carefully inside road tunnels than the others.

The aforementioned studies indicate the need for addressing the lack of knowledge that a significant part of drivers exhibits. To do so, efficient information campaigns and tools should be developed. Besides, Ntzeremes and Kirytopoulos (2018) pinpoint the crucial role of the behavior of trapped users in case of a fire accident. Modelling the evacuation process of trapped users, the authors argue that only a small delay during the evacuation process can be fatal for the users.

2.2. The use of VR technologies in tunnels

Taking the above into consideration, the need for better training methods for tunnel driving becomes apparent. Studies have shown that the use of serious games has been useful in improving various aspects of driver behavior, such as on safety awareness (Vera et al, 2017), on spatial cognition (Masoumzadeh and Moussavi, 2020), and on general driving habits (Yang et al, 2018). These findings indicate the use of a serious game as a logical tool for facilitating users' education.

In order to understand the mechanism of error evolution in road tunnels, the analyst needs to investigate both driver's behavioral factors along with tunnel system's factors that affect the overall driving error behavior. Studies utilizing

virtual reality (VR) technologies for road tunnels in the past have been sparse, making use of now-outdated forms of technology, and focusing almost exclusively on pedestrian behavior during evacuation scenarios. In brief, fire simulations in virtual tunnels have been studied by Ronchi et al., (2016), and the effect of lighting on evacuation behavior was the subject of a study by Domenichini et al., (2017), while Kinateder et al., (2014) studied the influence of conflicting information on evacuation behavior. However, none of the above research endeavors concern themselves with the driver's point of view in accident situations and the events leading up to a road tunnel accident. It was generally observed that VR has not been extensively utilized in road tunnel research as it has been done in other sectors with very encouraging results (i.e. process industry, Plot et al., 2010), and as such a complete and extensive simulation of a road tunnel environment does not currently exist. Moreover, the potential of VR systems as a training tool for driving in road tunnels remains widely unexplored.

3. Method

The approach of the research team in tackling the aforementioned issues is based on the idea of "serious games". The general idea is the development of a complete simulation environment of driving through a tunnel, using the Unity Game Engine.

The reasons for which this method and tools were chosen, is manifold. Firstly, training via serious games is nowadays explored in many fields as there is an expectation that it can actively increase knowledge acquisition and retention, as compared to traditional forms of education. The idea is that such kind of education will enhance the main existing form of education which is the informational pamphlets usually offered by highway authorities. To further capitalize on this effect, the use of VR technology was deemed reasonable, in order to increase the users' immersion in the simulation as compared to usual video games. The Unity Game Engine was chosen as a development environment due to its ease of use, abundance of free resources, and the fact that it very easily facilitates the conversion from conventional video game format to VR environments.

The environment is based on the typical one way tunnel setting that is mostly found in Greek highway roads and is the standard in most European countries for newly constructed tunnels. Namely, the tunnel is approximately 2km long, with two driving lanes, and three emergency exits along its length, one every 500m. There are emergency phones and fire equipment placed every 250m along the length of the tunnel, as well as Variable Messaging Signs (VMS) at the midpoints between emergency exits.

Within that simulation, various different scenarios, representing typical cases of driving through tunnels, were developed and examined. The overall aim is the creation of a software tool to help educate and inform potential users on the specific rules and behavioral patterns that should govern driving through tunnels. The developed scenarios were based on the research team's previous knowledge of these specificities of tunnel driving, acquired through previous research such as Kirytopoulos et al. 2020, Ntzeremes & Kirytopoulos, 2018, Kirytopoulos et al. 2017, etc. Within that research, the relevant standards and proper behavioral patterns, along with the specific needs for education (i.e. areas that tunnel users lack knowledge), have been explored, allowing the research team to determine a comprehensible set of instructions that tunnel users should follow in different cases of driving through tunnels, ranging from a simple uneventful drive to extreme cases such as an accident or a fire within the tunnel. This in turn allowed for the development of the relevant simulation environment, with special focus on demonstrating these instructions to potential users.

The general format of the environment consists of a first-person driving simulation, akin to a racing game. The user begins the simulation inside their car, and is prompted to drive through the tunnel, where different situations might occur depending on the scenario being examined. Within the car, there is also a number of elements, which the user can interact with, affecting their experience of driving through the tunnel. These elements were selected according to the aforementioned rules and standards, and correspond to actions that a driver should undertake when driving through a tunnel in reality. These elements are:

- The car key
- The radio
- The driver window
- The front lights
- The warning lights
- The air circulation button
- A pair of sunglasses

Finally, within the car, there is also a fuel indicator as well as a speedometer which the user can see while driving. These elements, while not being "interactive", should also affect the user's behavior within the simulation.

In addition to the features contained within the car, the simulation also incorporates various changing elements within the tunnel itself. The user cannot directly interact with these elements, but they represent external variations to the driving situation to which they should react accordingly. These elements include:

- Lane control signs
- Traffic lights
- Variable-message signs (VMS)
- Speed limit signs
- Emergency exits
- Fire equipment
- Emergency phones

Finally, the simulation also contains a messaging system, which displays instructions or suggestions to the user while they drive through the environment, illustrating the "recommended" course of action according to the instructions mentioned above. This system can also be

deactivated in order to examine the users' decisions in the absence of outside guidance.

4. Proposed tool

4.1 Scenarios examined

In this section the first scenarios developed within the simulation environment are explained in detail, illustrating the similarities and differences between them as well as what information each of them aims to provide regarding drivers' behavioral patterns.

1) Drive-through

In this scenario, the user starts within the car, at a distance of approximately 1km from the tunnel. They encounter various signs while approaching, indicating that a tunnel is ahead, the next gas station is beyond the tunnel, and what the speed limit is. Simultaneously, messages are shown to the user, reminding them of the actions required while driving through tunnels. Namely, the user is prompted to observe speed limits, ensure they have sufficient fuel to traverse the tunnel, remove their sunglasses and turn on their headlights. When the user reaches the tunnel, the messages stop, and the user is allowed to drive through the tunnel uneventfully. The tunnel's lane control signs remain green throughout the scenario, and the VMS read "Drive Safely".

2) Red Traffic lights within tunnel

This scenario begins similarly to the drive-through described above, with the user receiving basic instructions on how to act while driving through the tunnel. However, in this case, while the user is about halfway through the tunnel, the lane control signs turn from green to red, as do the traffic lights. A message is shown to the user reading "Red lights ahead, stop". If the user decides to violate the red light, they are once again shown a message reading "You just passed a red light. There is a fine for that, you know", and they are considered to have failed. If the user stops their vehicle and waits for 30 seconds, they are prompted to turn on their car radio by the messaging system. In doing so they can hear that there has been an accident in the tunnel, and the traffic has been stopped. The user is then considered to have successfully completed the scenario. In future development versions, the lights will turn green again, indicating that the obstruction has been handled, and the user will be allowed to finish their drive-through of the tunnel.

3) Heavy smoke from the engine

In this scenario a case of vehicle failure is examined, as well as a fire hazard. The beginning of the scenario is virtually identical to the above two cases, with the slight difference that the user is forewarned at the beginning that they will be experiencing a case of fire. In this case, while the user is driving through the tunnel, thick black smoke starts coming out of the car's engine, obstructing the user's vision. The messaging system displays "There's smoke coming from the engine! " in order to prompt the user to take action. If the user continues to drive, they collide with an invisible wall, and the messaging system informs them that they have crashed. The car's control is deactivated, disallowing the user to take any further action, and they are considered to have failed. The action that the user is expected to take, is to stop the car at the right side of the road, or on the sidewalk. If they do so, the messaging system displays that this was the correct choice, and the user is considered to have successfully completed the scenario.

4.2 Scenarios implementation

In the following section each of the above scenarios' implementation will be explained and displayed with screenshots.

In the below screenshot (Figure 1), one can see the "checkpoints" or "triggers" that the user needs to pass in order to see the various messages.

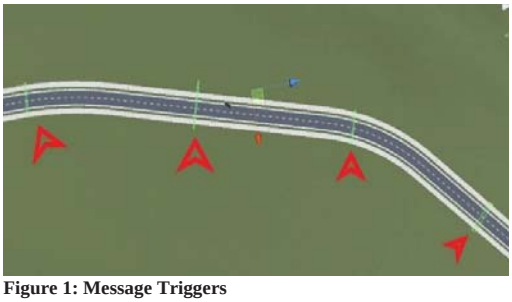

Figure 1: Message Triggers

This is the logic used in all scenarios described above; assuming that the user drives on-road and tries to enter and exit the tunnel, they will inadvertently enter these trigger spaces and view the relevant messages, or initiate the related events.

In Figure 2, the interior of the tunnel is visible, as it appears to the user during the drive-through. As described above, all lane control signs and traffic lights are green, and VMS boards read "Drive Safely"

Figure 2: Standard Tunnel Situation

In Figure 3, the case of red lights occurring in the tunnel is shown.

Figure 3: Red Lights in Tunnel

The user has to stop, otherwise they are shown a chastising message (Figure 4), and they have failed the goal.

Figure 4: Red Light Ignored

When the vehicle stops, and after 30s, the user is shown the message to check their radio, which they can do by clicking on the corresponding button (see Figure 5). Then they hear a message that an accident has taken place therefore the traffic is stopped.

Figure 5: Check Radio Prompt

In Figure 6 the scenario with the smoke coming from the engine is visible, and it becomes apparent that the user's visibility is heavily obstructed. In this scenario the user is expected to stop his vehicle immediately.

Figure 6: Smoke from the Engine

Figure 7: Waiting on Sidewalk Prompt

If the user continues driving instead, they crash as shown in Figure 8 and they are considered to have failed. The vehicle stops functioning, and the user can drive no further.

Figure 8: Crashed Prompt

4.3 Scenarios usage

All of the simulation scenarios described above can be used in a number of ways, depending on the intended result. In each of the three, the messages displayed to the user have been chosen and developed by taking into consideration the instructions and guidelines that a user should receive in regards to the specificities of driving through tunnels, and aim to demonstrate to the user the correct decisions and course of action that they should take in such a situation, while also illustrating the negative outcomes of incorrect decisions. As such, they can be used as a form of "basic training" for users that do not have the experience of driving through tunnels, in order to help familiarize them with such situations. This constitutes an important addition to driver training which traditionally contains little to no training relevant to tunnel driving.

On the other hand, by deactivating the messaging system these scenarios can be used as an evaluation system for users who already have tunnel driving experience. Without the specific prompts, the researchers can determine whether a user remembers to take the appropriate actions before and during their drive-through of the tunnel, as well as their reaction to the simulated emergency situations. Since deactivating the messaging system can be done autonomously, all other functionalities of the simulation remain in place, including any "penalties" for incorrect decisions. This allows the users to experience the consequences for failing to take the appropriate actions in each situation, as they would in a real-life driving situation.

5. Conclusions and further research

The present research is centered on the development of a training and evaluation tool for improving driving behavior in tunnels. By combining the research team extensive previous experience in the field, with an approach based on serious games, which offers various advantages for educating and evaluating users, it is the aim of this research paper to instil in users a better understanding of the circumstances and rules of driving through tunnels, with the overarching goal of increasing road safety.

On the limitations side, the researchers are seriously considering some critique that exists regarding the effectiveness of simulation training and aspire to test the effectiveness in the future, specifically in the context of road tunnels.

The next steps for this research include the development of various other scenarios (such as accidents, fire situations, and conceivably evacuation scenarios), which will encompass a variety of emergency situations within tunnels. Afterwards, the developed tool will be used as a training simulation tool on both experienced and inexperienced drivers. This task will provide critical insights on which areas the tool can be improved, as well as indicate whether it is an effective training method. Furthermore, there is also the plan to incorporate the entire environment into a VR setting, which will greatly increase the realism and immersion of the training simulation.

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