Robotics and Road Transportation: A Review

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Abstract. In this paper a critical review of road infrastructure and vehicle robotic technologies is presented. It is found that many infrastructure-related robotic technologies have not reached the implementation stage, which is attributed to reliability concerns as such technologies involve high risk operations such as crack sealing. However, that the greatest effort to robotize operations in road transportation has been aimed at getting driver assisted and autonomous vehicles. The use of a crash avoidance system to prevent the impact of a double tractor-semitrailer truck onto a scholar bus is further analyzed, finding that a longitudinal crash-avoidance robotic system might have saved as many as seven lives. It is found that the main limitation of autonomous vehicles has to do with their ability to recognize atypical road irregularities that might endanger driving.

Keywords: Robotics, road transportation, road crashes, lateral stability, directional stability, autonomous vehicles.

1 Introduction

Road transport externalities include the social and economic consequences of crashes and the multidimensional effects of pollutants emitted by motor vehicles. On the road safety side, each year approximately 1.3 million people are killed on the roads while 20 to 50 million individuals result injured [1]. On the other hand, emissions of toxic gases due to transportation represent a real threat to sustainability [2] [3], with congestion and driving style representing prominent influential factors [4].

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In this context, since the very beginning of motorized road transportation, electromechanical systems have been designed and implemented to increase driver and passenger comfort, road safety and fuel efficiency of engines. Examples of such early developments include electric windshield wipers (1939), antilock brakes (1971) and computer-controlled fuel injection engines (1976) [5]. Further improvements in electronics and mechanical devices resulted in systems with a broader range of functions representing different levels of intervention and automation, aiming to increase road safety and fuel efficiency. In this context and in a wider sense, robotics has been considered among the space-time adjusting technologies, as a result of improvements in automation and efficiency in the transportation infrastructure [6]. In this paper, a critical literature review of road transportation robotic technologies is presented, focusing on road safety, fuel efficiency and prevailing challenges.

2 Infrastructure-Related Robotics

Robots have been designed to perform operations for building and maintaining infrastructures, such as excavation works [7] and unmanned construction [8]. Robotic devices for road construction and maintenance have evolved since the first description made by professor Dah-Cheng Woo in 1995 [9]. At that time, a wide scope about the use of robots for construction and maintenance operations was conceived, focusing on areas of automated pavement inspection and crack sealing, automated bridge inspection and maintenance, automated bridge construction, and site integration. This last concept included, for example, the optimal earth moving operations. Future developments at that time included "accurate means to detect pavement distress at the earliest stage", robotic aids for working zones, underwater inspection of abutments and pier scours, and "sound and continuous operations for bridge painting and paint removal" [9]. In 1992, the Strategic Highway Research Program also recognized robotic operations for maintenance operations to identify, map, track and fill pavement cracks, involving sensors to specify crack length, size and depth [10].

Automation and robotics in construction in general, and road construction in particular, has represented a crucial interest to the construction industry as indicated by the creation of specialized associations such as the International Association for Automation and Robotics in Construction (IAARC) which publishes the Automation in Construction Journal and organizes the Annual International Symposium on Automation and Robotics in Construction. As a result of these activities, a diversity of estimations has been made on the future of robotics in the construction industry. In particular, Elattar lists the following developments [11]: automatic asphalt operations (reception, conveyance, spreading, paving, longitudinal crack sealing, roadside cleaning endeavors). In this respect, it is claimed that by robotizing these operations a better quality of the work will result while the workers will be less exposed to dangerous operations. Additionally, improved efficiencies are also thought to be the potential result of robotic earth moving operations, involving a variety of sensors to minimize the number of earth moving operations for a certain volume of material. Nevertheless, the main technological limitation for these robotic earth-moving operations derives from the complexity to model machine – soil interaction as a result of the plurality of factors that affect soil properties, including moisture content, stress history, time and environmental conditions [12]. Failed infrastructures have also been the subject of robotic approaches as in the case of rescue and surveillance operations [13].

Robotic total stations have been used for scanning and producing 3D models for construction and upgrade projects [14], or to inspect bridges [15]. To prevent road workers exposure, robotic highway safety markers have been proposed and tested [16] [17] [18]. Under different principles of operation (Lasser, global hearthbeat), these robotic systems provide accurate means to position barrels along the road work areas without exposing workers to accidents. Constraints for these designs include stability under wind loads, climb slopes and low cost [17].

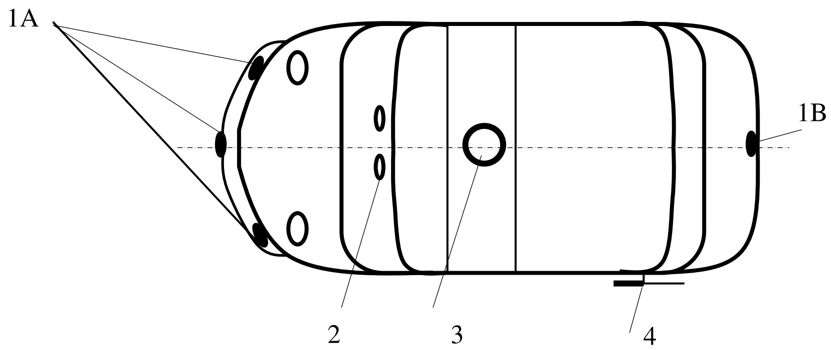
Unfortunately, in spite of the numerous studies and prototypes there is no evidence that these work zones technologies have been actually deployed.

3 Computer Aided Driving

Robotics in vehicles involves different levels of intervention of the robotic system for the operation of the vehicle with the purpose of preventing crashes, increase comfort or to save fuel. The maximum level of intervention of the robotic system is represented by autonomous vehicles, which do not need a driver to circulate even under normal traffic conditions, with assisted driving providing some aid to the driver during specific situations.

The maneuvers that have been robotized and that have been incorporated into commercial vehicles include the following: Parallel Parking (PP), Automatic Cruise Control (ACC), Crash or Collision Avoidance (CA), Overtaking or Passing Maneuvers (OPM), rollover prevention, and lateral vehicle guidance. While such systems have been incorporated into cars and light trucks, heavy trucks represent in general different conditions leading to a crash. Particularly, articulated vehicles can get into lost control situations such as the jackknifing or rollover. For trucks, the following vehicular stability systems have been developed [19]: (i) the Roll Stability Control (RSC), which is a system that automatically intervenes to assist the driver to avoid a rollover through reducing the throttle and potentially applying the engine brakes; and (ii) the Electronic Stability Program (ESP) which controls vehicle´s oversteer or understeer through automatically controlling the throttle and selectively activating brakes to eliminate such instability condition. Safety systems to control the vehicle under emergency situations thus include rollover and steering stability considerations [20]. Active safety systems comprise the Electronic Stability Control (ESC) and the Active Front Steering (AFS), under an integrated scheme. However, brake control can also be used to prevent rollover risk situations, through the combination of real time data with simulation information about the precise moment at which the rollover might occur [21]. Such a system is based on a Linear Parameter Varying model (LPV) of yaw-roll dynamics of heavy vehicles that include the prediction of critical values while monitoring the lateral load transfer.

Advanced robotic applications include the Fully Adaptive Cruise Control system (FACC), which takes into account even the driver´s preferences that define his/her driving style [22], involving a learning process of driver´s attitudes and preferences. The purpose of a FACC system is to maintain a certain pre-calibrated distance with respect to the vehicle traveling ahead, regardless of the speed changes of that vehicle. Other advanced robotic devices consist of the CAS CWS systems (Automatic Cruise Control, Collision Avoidance Systems and Collision Warning Systems), for which it is necessary to have reliable information about the kinematics of the vehicle [23].



Parts:

1A, 1B	Radar sensors, determine the position of distance objects;
2	A camera near the rear-view mirror to detect traffic lights and helps the car´s onboard computer recognize moving obstacles like pedestrians and bicyclist;
3	Rotating sensor on the roof scans more than 200 feet in all directions to generate precise three-dimensional map of the car´s surroundings;
4	Sensor on the left wheel measures small movements made by the car and helps to accurately locate its position on the map.

Fig. 1. Autonomous car. Figure made using information from Markoff (2011) [25]

An assisted driving vehicle can become an autonomous, robotic vehicle once the different detection, cognition and acting systems govern the steering, braking and acceleration controls of the vehicle. Autonomous systems can also be used for the purpose of controlling the path of a vehicle when following another vehicle [24]. Figure 1 illustrates an autonomous vehicle that has been recently tested at a prototype level, listing the set of sensors needed to drive the vehicle under normal traffic conditions [25]. As it can be seen in this figure, this design combines different technologies to locate the vehicle within the space and to identify the objects in such space. It includes a geographic positioning system as well as cameras, radars and inertial references. Developers of this vehicle do not point out whether the vehicle is able to recognize road profile to detect bumps, potholes and other pavement disturbances which might affect vehicle´s stability and integrity. While the elements and sensors in this vehicle recalled those used by other car manufacturers that have participated in sponsored events by the Defense Advanced Research Projects Agency (DARPA) it seems that recent developments are more compact and less cumbersome.

Efforts to provide autonomy to trucks have been limited to some functions and operations such as longitudinal speed control, lane position detection and control, and turning at low speed (40 km/h) [26]. As far as the fuel consumption of heavy trucks is concerned, optimized geographic information algorithms have been considered to control the throttle position during changes of road geometry [27]. In particular, an intelligent system has been proposed to minimize fuel consumption during flat to uphill transitions, through the estimation of power demand and by controlling the throttle position [28].

In this context, the technological complexities associated to the creation of autonomous vehicles derive from the change of environments, including “un-engineered” environments subject to sudden changes [29].

3.1 Robotic Vehicles and Professional Associations

The Society of Automotive Engineers (SAE) classifies the level of robotic intervention as follows [30]: autonomous vehicles, collision avoidance, electronic control systems, intelligent vehicles, and total vehicle integration. In 2009, SAE created the Standards Technical Committee AS-4 named Unmanned Systems, including four subcommittees focusing on architectural framework, network environment, model and performance measures. There is also the ITS (Intelligent Transport Systems) safety and human factors technical committee [31]. The Transport Research Board (TRB) includes the AHB30 committee to cover topics dealing with the Highway Automation, Intelligent Transportation Systems (AHB15), and Vehicle User Characteristics. There is the TRB´s Committee on Artificial Intelligence and Advanced Computing, Emerging technology law, Unmanned ground vehicles, Autonomous vehicles, Vehicle platooning, and vehicle platoons [32]. In a worldwide context, there is the Association for Unmanned Vehicle Systems International (AUVSI), which locates different State of the Art centers for autonomous road vehicles in different countries: four in The United States, two in Germany, and one in each of the following countries: Sweden, Italy, United Arabic Emirates, Australia, Japan and China [33].

While these organizations seem to cover all of the technical aspects related to driverless cars and robotic applications in road transportation, an important topic seems to be needed to be addressed, which is the circulation on damaged roads, as driverless vehicles do not have the ability to detect and to response to potholes and other pavement defects [34].

3.2 Autonomous Vehicles and the Law

In the United States of America three States, New Jersey, Nevada and California, have recently introduced the term "autonomous vehicle" to promote the use of such technologies. In the case of the State of New Jersey, the respective standard defines the following [35]: ""Autonomous vehicle" means a motor vehicle that uses artificial intelligence, sensors, global positioning system coordinates, or any other technology to carry out the mechanical operations of driving without the active control and continuous monitoring of a human operator". The State of Nevada legislation, however, recognizes such autonomy as an operational mode, allowing self-driving automobiles provided the use of a special red license plate and the payment of an extra insurance bond [36]. In the State of California a law will take effect on January 1, 2013, allowing driverless cars to be operated on public roads for testing purposes [37]. While these regulations refer to "autonomous vehicle", commercial publications use the term "Driverless cars" [36], which is not exact in the sense that autonomy of the vehicle is a non-permanent mode of operation, that is, legislation assumes a potential driver in the vehicle who can take control of it under special circumstances.

Regarding assisted driving, in May 2012 the National Highway Traffic Safety Administration (NHTSA) proposed a Federal Motor Vehicle Safety Standard (FMVSS) to mandate the preferential use of the Electronic Stability Control (ESC) over the Roll Stability Control systems (RSC), on all new trucks with a weight greater than 26000 pounds [38]. Although such preferential criteria was the result of several studies and statistical analyses, the American Transportation Research Institute (ATRI), has pointed out that ESC systems are less effective and more expensive than RSC systems [39]. While there is no doubt about the positive effect of using any of these technologies, apparently there is still discussion about which system represents the greater cost-benefit ratio.

3.3 Advantages and Disadvantages of Autonomous Vehicles

It has been argued that autonomous technology could enhance road safety and fuel efficiency, in addition to a potential economic development. However, the main issue here is the needed enhanced liability [25]. In spite of the open interests that different institutions and organisms have demonstrated toward the development of autonomous vehicular systems, it has been argued that such systems do not necessarily represent a road safety improvement, as drivers that might get used to automatic driving will be less aware and responsive than if they were in permanent control of the vehicle [36].

On the other hand, in addition to the potential safety improvements due to robotized vehicles, it has been argued that driverless systems could become so reliable that other activities could be performed while traveling so that such activity would not be a waste of time anymore [40]. In this respect, users of autonomous vehicles could communicate through cell phones, whether through SMS or call [41].

Potentially, repercussions of having autonomous vehicles include the capacity of roads and even vehicles´ design. While larger road traffic capacities are expected as shorter gaps between cars could be possible, a diminished crash probability would signify to build lighter cars that consume less fuel. Less accidents with autonomous vehicles is expected as such vehicles would not get fatigued nor fell asleep or get intoxicated, in addition to having a faster reaction time than humans and a better, 360 degree perception [42].

However, autonomous vehicles face difficulties to avoid crashes as there are multiple scenarios for crashes. In the case of bus transit, Dunn et al. [43] recognize at least 60 different collision scenarios, involving seven collision warning for object detection systems.

4 Crash Prevention Potentials

A scenario is described to analyze what would be needed from the autonomous vehicle technologies perspective to avoid a tragic road crash. On the morning of April 12, 2012, a double tractor – semitrailer combination (DTSC) crashed onto a bus carrying 36 university students while negotiating a turn on a 2.2% downgrade three-lane Mexican highway. 7 people died at the spot while as many as 10 suffered grave disability (e.g., no arm). It was reported that the DTSC truck had lost its brakes, accelerating the truck out of control and causing the failure of the trailer´s double-axle dolly, centrifuging it onto the scholar bus. Part (a) of Figure 2 describes a 2.5 s potential kinematics for such a crash, assuming a constant speed for the vehicles. According to the timeline shown in this figure, it took less than two seconds for the DTSC to hit the bus from a starting position 20 m behind it. To prevent this crash, actions could have been taken on the DTSC or on the bus. For the DTSC, the use of positive engine-linked braking systems could have functioned to stop the full vehicle once the brake malfunction was detected. On the bus side, evasive and accelerating maneuvers could have been executed, whether separately or in conjunction. Apparently, the bus driver was not aware of the coming out-of-control DTSC, and no reaction from him took place. On the one hand, in order to perform such a crash-avoidance maneuver through a robotic vehicle, the bus should have been equipped with 360° radar sensors in order to detect the coming vehicle, further assessing the available space for the crash avoidance steering maneuver. Additionally, the other action that might have been taken by the robotic system on the bus could have included an energetic acceleration, aiming to diminish the relative DTSC-bus speed and, if possible, get out of the trailer´s way. The time available for these two crash-avoidance maneuvers is less than 2.5 s. In this regard, it is taken into account that accelerating is the faster response to avoid a crash as it represents shorter processing time [44]. Consequently, part (b) of Figure 2 illustrates the possible acceleration maneuvers that could have avoided this fatal crash, assuming an acceleration of 1.5 m/s^2 for the bus once the radar system detects the truck. Such an acceleration maneuver could have been feasible for the bus, as starting accelerations on zero slope roads can be up to 2.5 m/s^2, according to graphs presented by Rakha et al. [45]. For such maximum attainable acceleration, an additional safety gap could have been even gained in this case.

5 Discussion

The impetuous institutional impulse given to the creation and developing of autonomous cars, represented by multiple institutional and academic endorsements, suggests that such vehicles will become a technological reality in the near future. However, the cost of such equipment can be a problem, resembling a parallel situation with another development such as the hybrid traction systems, which are still not affordable for the gross of the population. A big difference between these developments, however, which might impulse autonomous vehicles technologies, resides in the fact that such technologies cross many critical transport issues such as safety and fuel economy. Another impulse to these technologies can be gained from the need to assist an ageing population that would wish the mobility independence provided by cars. In this respect, robotics in cars takes a new dimension, being part of the overall picture of population´s future mobility.

6 Conclusions

Robotics in road transportation has encompassed many critical safety-related areas from construction and maintenance of infrastructures (road and bridges) to vehicles operation. Although infrastructure operations were the subject of many early academic and government endeavors, this review shows that no significant technological deployment has occurred. On the other hand, autonomous vehicles have gained industrial momentum recently as a result of emerging technologies such as the precise and reliable global positioning systems, and rapid image processing. In this respect, incorporation of robotic systems into road transportation has evolved from relatively simple operations to fully autonomous vehicles in which the vehicle becomes the robot itself. The social acceptance of such technological developments is demonstrated by the issuing of standards and laws for such advanced vehicles. However, unresolved technological issues are related to the detection of atypical infrastructure defects such as open manholes and other road perturbations, which might represent major road safety hazards. In this context, autonomous vehicles could also be a mobility alternative to a growing aged population. The analysis of a crash involving a scholar bus revealed that a robotic longitudinal crash avoidance system might have saved many lives or diminished the gravity of its effects.

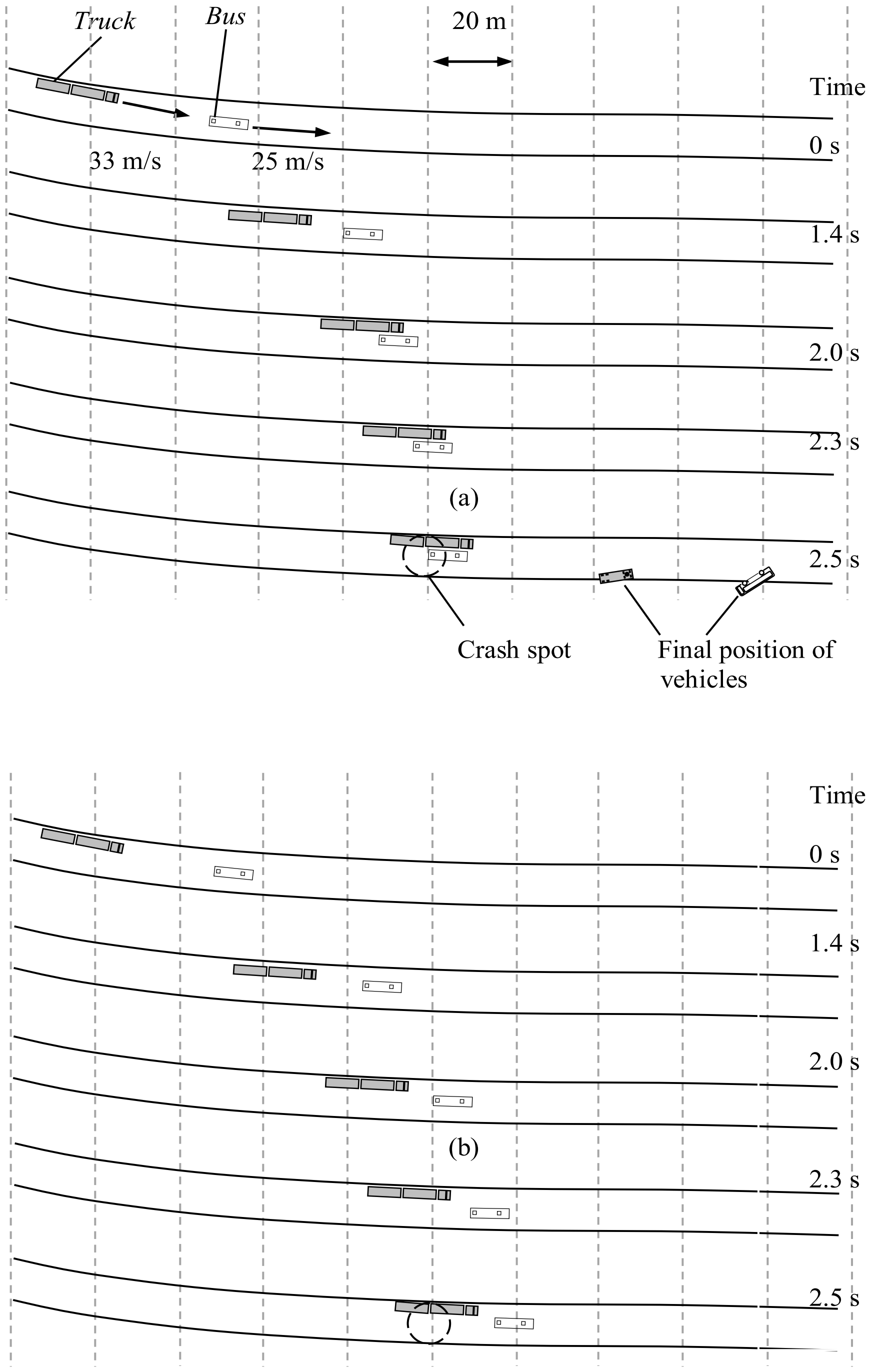


Fig. 2. Potential crash sequences: (a) Crash occurrence situation; (b) Crash-avoidance situation

Robotic longitudinal crash avoidance systems might thus represent a meaningful means to increase road safety at a short term. While cars have been the main focus of robotic technological developments so far, the implementation of autonomous heavy trucks would represent a major challenge as far as the liability is concerned, but with potentially enhanced benefits.

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