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A surface electromyography controlled steering assistance interface

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Abstract
Purpose – Two-handed automobile steering at low vehicle speeds may lead to reduced steering ability at large steering wheel angles and shoulder injury at high steering wheel rates (SWRs). As a first step toward solving these problems, this study aims, firstly, to design a surface electromyography (sEMG) controlled steering assistance interface that enables hands-free steering wheel rotation and, secondly, to validate the effect of this rotation on path-following accuracy.

Design/methodology/approach – A total of 24 drivers used biceps brachii sEMG signals to control the steering assistance interface at a maximized SWR in three driving simulator scenarios: U-turn, 90° turn and 45° turn. For comparison, the scenarios were repeated with a slower SWR and a game steering wheel in place of the steering assistance interface. The path-following accuracy of the steering assistance interface would be validated if it was at least comparable to that of the game steering wheel.

Findings – Overall, the steering assistance interface with a maximized SWR was comparable to a game steering wheel. For the U-turn, 90° turn and 45° turn, the sEMG-based human–machine interface (HMI) had median lateral errors of 0.55, 0.3 and 0.2 m, respectively, whereas the game steering wheel, respectively, had median lateral errors of 0.7, 0.4 and 0.3 m. The higher accuracy of the sEMG-based HMI was statistically significant in the case of the U-turn.

Originality/value – Although production automobiles do not use sEMG-based HMIs, and few studies have proposed sEMG controlled steering, the results of the current study warrant further development of a sEMG-based HMI for an actual automobile.

Keywords Advanced driver assistance systems, Human–machine interface, Myoelectric control system, Path-following, Steering assistance system, Surface electromyography

Paper type Research paper

1. Introduction

Sometimes drivers have to steer sharply and rapidly at low vehicle speeds to maneuver in confined spaces such as narrow roads and crowded parking lots (Takada et al., 2013). However, rapid, two-handed steering subjects the shoulder of the driver to high forces that may cause injury. If the steering wheel is rotated to the right with two hands from 0° to 65°, with an average time of 0.268 SD 0.065 s, healthy supraspinatus and deltoid muscles are subjected to forces that could lead to muscle overload (Pandis et al., 2015).

The risk of injury is compounded by another issue at low speeds, namely, a decrease in the ability of the driver to turn a steering wheel, i.e. decreased steering portability. Primarily because of the reaction forces between the tires and the road, the torque required to steer the road wheels is maximized when an automobile is moving slowly or at a full stop (Ma et al., 2016; Sharp and Granger, 2003). Consequently, when the steering wheel is manually rotated from the neutral position to 300° or higher, the ability of the driver to rotate the steering wheel decreases rapidly (Ma et al., 2016).

As a means of preventing decreased steering portability and reducing the risk of shoulder injury, a steering assistance interface that relies on surface electromyography (sEMG) input from the biceps brachii muscles has been developed to produce rapid, hands-free steering wheel rotation for low speed, nonemergency driving tasks. Because the interface was designed to rotate steering wheels faster than healthy drivers, the major driving task of curve negotiation could have been significantly affected (Pauwelussen, 2015). The path-following accuracy of the interface during curve negotiation was thus validated by driving simulator trials at different steering wheel rates (SWRs). The fastest SWR setting was associated with acceptable path-following accuracy that was comparable overall to a game steering wheel.

The applications of previous steering assistance systems and how they differ from the current application are detailed in the next section. Section 3 offers an overview of the design of the steering assistance system and the adaptation of the system.
interface to a driving simulator. Section 4 describes how drivers performed turning maneuvers with the interface so that the resulting trajectories could be used to determine path-following accuracy. A comparison in Section 5 is conducted between the interface and the game steering wheel with respect to path-following accuracy. Although the results of this comparison validate the accuracy of the steering assistance interface, there are limitations in this study that are conveyed in Section 6. Nevertheless, the results warrant further interface development, as recommended in Section 7.

2. Related work

Steering assistance has been implemented in production automobiles in the form of power steering systems (Shimizu and Tokunaga, 2015). Power steering relies on a control scheme in which the driver rotates the steering wheel with assistive torque from the power steering system (Takada et al., 2013). Some vehicles use electric power steering (EPS), whereas other vehicles use an alternative form of steering assistance called “active front steering” (AFS) that automatically decreases the steering ratio when vehicle speed decreases (Kumar, 2012; Li et al., 2014). Both EPS and AFS have been developed to improve steering portability at low speeds.

The development of automated driving systems has expanded the design direction of steering assistance to vehicle safety (Chan, 2017). Until the present decade, steering assistance as a collision avoidance technology was investigated but not featured in production automobiles (Dang et al., 2012). Nevertheless, research has led to some advanced driver assistance systems that can be classified by the level of automation as driver-initiated evasion assistance, corrective evasion assistance and automatic evasion assistance (Dang et al., 2012). Driver-initiated evasion assistance systems use sensors such as cameras or radars to detect road obstacles ahead of a vehicle. A driver indicates the intent to avoid a road obstacle through steering wheel movements that are recognized by the steering assistance system. Support is then provided by a steering actuator that applies torque to the steering wheel to guide the driver around the obstacle. On the other hand, corrective evasion assistance directly initiates steering in situations where braking will not prevent collision. Automatic evasion assistance is the most automated system because it directly initiates steering maneuvers in accordance with various collision avoidance scenarios.

Aside from collision avoidance steering systems, nonemergency steering assistance has been featured on production vehicles to optimize lane-keeping and path-following accuracy. The Nissan ProPILOT Assist is one example that provides small steering corrections to improve lane-keeping on highways (Dinh and Kubota, 2013). Turn Assist is another type of steering assistance that supports path-following along off-road trajectories with small turning radii.

In contrast to past technologies such as AFS, driver-initiated evasion assistance and Turn Assist, the steering assistance interface in the current study allows the driver to directly initiate a turn without holding the steering wheel. The sEMG signals generated from the electrical muscle activity of the driver are converted by the vehicle computer into control signals for a steering motor that is connected to the steering wheel (Figure 1). Consequently, the steering wheel is rotated at a constant SWR. The steering wheel could be mechanically linked to the front wheels through a steering column or through a steer-by-wire connection that relies on the vehicle computer to convert steering wheel rotation into electric actuator signals that steer the road wheels (Ackermann, 1997).

Biceps brachii sEMG signals from the right arm execute rightward turning maneuvers, whereas the sEMG from the biceps brachii of the left arm executes leftward turning maneuvers. Surface electrodes that sense these signals and the equipment that converts the signals into steering wheel rotation constitute the human–machine interface (HMI) of the steering assistance system (Figure 1). HMIs enable interactions between humans and machines. Examples include computers that allow operators to control machining devices and equipment for offshore drilling (Martinsen et al., 2016; Strand and Lundteigen, 2017). Other interfaces allow sEMG to control prosthetic limbs and other devices (Basmajian and De Luca, 1985; Hakonen et al., 2015). HMIs involving gestures that produce sEMG signals have been investigated for the purpose of navigating computer screen icons, inputting keyboard commands and controlling a robotic arm (Nagata et al., 2007; Tuisiku et al., 2012). The existence of these interfaces indicates that sEMG is a versatile HMI technology.

HMIs that use sEMG have been proposed for controlling different types of vehicles. Facial gestures produce myoelectric signals that enable people to control wheelchairs (Felzer and Freisleben, 2002; Rivera and Desouza, 2012). Myoelectric signals from hand gestures have been used to control a model military tank (Takizawa et al., 2009). Despite the existence of various sEMG controlled devices, there are only a few studies related to sEMG controlled automobiles (Kwak et al., 2008; Nacpil et al., 2018). The current study advances the application of sEMG to automotive control systems by investigating a sEMG controlled steering assistance interface.

3. Design of the steering assistance system

One design objective of the steering assistance system is to enable hands-free steering wheel rotation to prevent decreased steering portability when a vehicle travels at low speeds of 30 km/h or less or at parking speeds near or equal to 0 km/h (Dinh and Kubota, 2013; Sharp and Granger, 2003). Hands-free rotation also meets the design objective to reduce the risk of...
shoulder injury resulting from rapid two-handed steering (Pandis et al., 2015).

Considerations regarding the control design and operation of the steering assistance interface are provided in Section 3.1. Although the steering assistance system was intended for an actual automobile, path-following accuracy was validated with a driving simulator for the safety of the test subjects and to identify how the interface could be improved prior to further development. The adaptation of the interface to a driving simulator is discussed in Section 3.2.

3.1 The steering assistance interface
Consideration was given to the possible ways in which myoelectric signals could be measured. There are multiple gestures with corresponding sEMG signals that could be assigned to steering maneuvers (Nacpil et al., 2018). In a previous study, a radio-controlled model vehicle was successfully steered to the right by supinating the right forearm (Takizawa et al., 2009). Because the biceps brachii is one of the most active muscles when the forearm supinates with the elbow flexed at 90°, the sEMG of the biceps brachii was selected to readily control the steering wheel angle (SWA) of the simulated vehicle (Bader et al., 2018).

If the proposed steering assistance system were to be implemented in an actual automobile, the steering control system design would use sEMG data acquisition equipment, as shown in Figure 1. Gesture-sensing technology that is functionally similar to commercially available technologies, such as the Myo Armband, would be worn on the left and right arms of the driver and would consist of dry electrodes that sense sEMG signals from the biceps brachii muscles[6]. Twisting the forearms through supination produces biceps brachii sEMG signals that are wirelessly transmitted by the armbands to signal processing equipment so that the signals are rectified and averaged. The signals are then converted to steering motor commands by the onboard vehicle computer.

For a steer-by-wire system, hydraulic power assistance at low vehicle speeds enables the steering motor to meet the increased steering torque demand at the front road wheels (Yih and Gerdes, 2005). If the steering wheel is mechanically linked to the road wheels with a steering column, some commercially available steering motors can meet the increased demand for torque by providing more steering wheel torque than human drivers (Forkenbrock and Elsasser, 2005; Sharp and Granger, 2003). Whether a mechanical or steer-by-wire connection is implemented, the SWA resulting from the steering motor would be relayed by an encoder to the vehicle computer so that steering motor commands are adjusted with respect to the measured SWA.

The flowchart in Figure 2 provides an overview of the operation scheme for the proposed steering assistance interface. Vehicle automation used by this scheme falls along a spectrum that ranges from Levels 0 to 5 (J3016, 2014). Level 0 automation requires the driver to perform all aspects of the dynamic driving task, i.e. acceleration, braking, steering and monitoring of the vehicle and roadway, whereas a vehicle with Level 5 automation performs the dynamic driving task without a driver. Because automobiles with Levels 4-5 technology can steer automatically, the proposed steering assistance would be redundant for these vehicles. In contrast, Levels 1-3 automation allows the driver and the vehicle to have shared control over steering. The current operation scheme applies to this range of automation, as the driver shares control with the steering assistance system.

The relation between the sEMG input of the driver and the rotational output of the steering wheel depends on the SWA that is conventionally represented as $\delta_H$ (ISO 4138:2012(E), 2012). If the steering wheel is at the neutral position, supination of the left forearm results in leftward steering wheel rotation until the maximum leftward SWA is reached (Figure 3). On the other hand, supination of the right arm results in rightward steering wheel rotation up to the maximum rightward SWA.

The steering assistance system uses a finite state machine (FSM) control scheme that converts sEMG input to the rotational output of the steering wheel (Figure 3). As in the case of past applications of FSM, such as prosthetic hands and power wheel chairs, the movement of the plant, i.e. the steering wheel, is divided into the following states:
- maximum leftward SWA, $-\delta_{H_{\text{max}}}$
- maximum rightward SWA, $+\delta_{H_{\text{max}}}$
- the neutral position, where $\delta_H$ is 0° (Cipriani et al., 2008; Felzer and Freisleben, 2002; Geethanjali, 2016).

If the amplitude of the average rectified sEMG from the driver exceeds a specified threshold, e.g. 30 per cent of the signal peak that is determined during the calibration of the sEMG armband to the driver, the vehicle computer determines which arm generated the sEMG signal (Figure 2). Based on the current SWA of the steering wheel, the vehicle computer then changes
the state of the steering wheel by sending a command to the steering motor.

Visual feedback is provided by the position of the driver relative to the surroundings of the vehicle (Land and Horwood, 1995; Land and Lee, 1994). When performing turns with small radii of curvature, for example, visual feedback from the road is used to maintain lateral distance between the driver and the lane marking of a curve (Land and Lee, 1994). Because this visual feedback is available in the simulated driving scenarios of the current study, other methods of steering feedback, such as vibrotactile devices, are not incorporated into the design of the steering assistance interface (Manawadu et al., 2017).

Because the proposed steering assistance is intended for controlling steering wheel states at low speed or parking speed, the maximum vehicle speed at which states can transition or be maintained without losing steering control is determined through simulation or actual vehicle testing (ISO 4138:2012 (E), 2012; Renfroe et al., 2007; Tandy et al., 2015). As a safety measure, if the maximum speed is exceeded when the steering assistance system is on, a sound notification is sent to the driver, such as a tone lasting several seconds so that the driver can resume manual control of the steering wheel (Figure 2). Note that the same notification would be sent if no signal is provided from the armband.

Before the steering assistance system is turned on, the driver confirms that the SWA is at or close to 0° and the vehicle is stationary. Thus, it would not be recommended to turn on the system in emergency situations, such as the instant before a collision, where there is no time to stop the vehicle and move the steering wheel toward the neutral position. When steering assistance is turned on, the driver lets go of the steering wheel so that the vehicle computer maintains the SWA at 0° (Figure 2). The driver could then supinate the forearms to rotate the steering wheel (Figure 3).

During the operation of the interface, there is a possibility that arm gestures intended for other tasks, such as the operation of the stereo, may produce sEMG signals that would inadvertently cause steering wheel rotation. Therefore, when the driver wishes to perform another task besides the rotation of the steering wheel, steering assistance can be deactivated by pressing an on/off switch at a convenient location such as the dashboard.
sEMG signals from the scalp. The sEMG-based interface was almost as accurate as the tractor steering wheel with respect to path-following.

Although sEMG technology is subject to its own set of potential problems, including electromagnetic interference, the use of signal filtering, bipolar electrodes and wireless sEMG signal transmission can mitigate some of the interference (Hakonen et al., 2015; Merletti et al., 2009). Further precautions such as an on/off switch and a torque sensor in the steering wheel for manual takeover are incorporated into the steering assistance system (Figure 2). By considering the advantages and disadvantages of various prospective interfaces, the sEMG-based interface has been selected to control the steering assistance system.

3.2 Adaptation to a driving simulator
The sEMG-based HMI was adapted to a driving simulator with a focus on ease of implementation (Figure 4). Components that comprise the sEMG acquisition equipment of the interface were chosen on the basis of affordability and, in cases where the components had to be designed and constructed, component complexity was minimized. Such a strategy was appropriate because the objective of the experiment was the validation of path-following accuracy rather than the complete implementation and testing of all HMI components.

An armband consisting of electrodes was to serve as the sEMG-based HMI for an actual automobile (Section 3.1). However, before investing time and effort in the development of the armband, a readily available and affordable substitute for the armband was used. Disposable Ag/AgCl bipolar electrodes were attached to the biceps brachii longhead, and a ground electrode was mounted on the wrist in accordance with the recommendations of SENIAM (Surface EMG for the Non-Invasive Assessment of Muscles) (Hermens and Freriks, 1997). Because the lateral portion of the biceps brachii belly provided a peak signal with the least variability in comparison to the medial and central portions, bipolar electrodes were placed along the lateral portion (Mercer et al., 2006). Bipolar electrodes were selected because they were more resistant to noise than other sensors such as monopolar electrodes (Hakonen et al., 2015).

Given that one design objective of the steering assistance system is to reduce the risk of shoulder injury to the driver during sudden two-handed rotation of the steering wheel to the right, all the simulated driving scenarios involved the rapid execution of rightward turning maneuvers (Figure 5) (Pandis et al., 2015). Consequently, only sEMG input from the right arm was used because the right arm exclusively controlled rightward steering (Figure 3).

In previous studies involving males and females, the median electromyography reaction time for the sEMG signal of the right arm biceps brachii was faster than that of the left arm by 3-4 per cent (Nakamura and Saito, 1974; Nakamura and Taniguchi, 1980). Because supination of the left arm rather than the right arm would add a negligible increase to the steering response time, it was expected that there would be a correspondingly negligible effect on path-following accuracy. Therefore, performing turns with the right arm alone was sufficient for path-following validation.

A custom sEMG data acquisition device (DAQ) was developed for the sEMG-based HMI (Figure 6). Control signals were processed with the DAQ and a Windows 10 platform laptop. (Panasonic CF-LX6 laptop with a 14-inch, 1920 × 1080 resolution screen.) The DAQ consisted of a custom circuit that applied filtering so that only analog signals with frequencies ranging from 2 to 530 Hz were amplified with a gain of 5,000. Amplified analog signals were digitized with a sampling rate of 10 kHz. The digital signals were rectified before applying a moving average with a window size of 50 data points. Then the signals were mapped onto an analog joystick control scheme with a sEMG amplitude of 0 corresponding to a centered joystick position and the peak amplitude corresponding to the maximum rightward joystick position. Because the driving simulator accepted keyboard commands, the laptop executed software to convert joystick commands into keyboard commands so that the steering of the driving simulator, Digital Battlespace 2™ (DBS2™, Bohemia Interactive), could be controlled. Whenever a test subject initially connected or reconnected to the DAQ, calibration of the DAQ was performed by using the game controller calibration software included with Windows 10. Based on this calibration, the threshold for sEMG control signals was set from 10 to 30 per cent of the peak signal resulting from forearm supination lasting up to 1 s. This setting prevented the detection of inadvertent sEMG signals and other interferences below the threshold.

As the test subjects operated the sEMG-based HMI, acceleration and braking were controlled with a set of foot pedals that originally came with the commercially available game steering wheel (Driving Force™ GT). The game steering wheel had force feedback and a steering ratio of 1:1 (Figure 7). As the steering of the driving simulator could be controlled without input from the game steering wheel, sEMG input controlled the steering in the simulator rather than the rotation of the game steering wheel.

In addition to using the steering assistance interface to complete the driving scenarios, the test subjects repeated the scenarios with the game steering wheel as a basis for comparison.

4. Experimental methodology
The objective of the experiment was to validate the path-following accuracy of the sEMG-controlled interface with a
driving simulator. If the use of the interface was associated with a path-following accuracy that was at least comparable to the use of the game steering wheel, then the sEMG-based HMI would be successfully validated.

Driving scenarios that were simulated in the experiment were constructed to test the interface with rapid SWRs at vehicle speeds below 30 km/h. The design of the scenarios and a general strategy for completing the scenarios with maximized path-following accuracy are detailed in Section 4.1. An experimental protocol for validating path-following accuracy is provided in Section 4.2.

4.1 Driving scenarios

As the steering assistance system was designed to reduce the risk of shoulder injuries posed by rapidly rotating the steering wheel to the right from 0° to 65°, all the simulated driving scenarios were designed to necessitate rapid SWRs and steering wheel rotation up to 65° to maximize path-following accuracy (Pandis et al., 2015). As a means of ensuring that this SWA would be necessary, the ideal trajectory in each scenario had a radius of curvature corresponding to the SWA. Given that the SWA corresponded to the smallest turning radius of the virtual car, the test subjects were instructed to only rotate the steering wheel up to the SWA. On the other hand, when test subjects used the sEMG-based interface, the virtual car would be steered to the turning radius at a constant SWR.

The need to rapidly rotate the steering wheel to optimize path-following accuracy was determined by the driving scenarios. Distance was allotted between the starting line in each scenario and the cone at the beginning of each turn (Figure 5). Test subjects were instructed to accelerate from the start line without braking or decelerating so that the speed at the beginning of the turn was nonzero. Because the ideal trajectory of the turn in each scenario had a radius of curvature equal to the smallest turning radius of the virtual car, it was possible to optimize path-following accuracy, if the steer angle of the road wheels corresponded to the smallest turning radius. This steer angle, i.e. the Ackermann steer angle, is a vehicle characteristic that applies to steady-state turning, where speed, SWA and the smallest turning radius are constant (ISO 4138:2012(E), 2012; Tandy et al., 2015). There is a transient phase prior to this steady-state in which the steering wheel rotates from the neutral position to 65°. A briefer transient phase entails that the Ackermann steer angle can be attained in less time. Therefore, the SWRs of the game steering wheel and the sEMG-based interface could be maximized to reduce the transient phase and to optimize path-following accuracy.

Aside from the Ackermann angle, a vehicle characteristic that is relevant to path-following is the steering-wheel angle gradient (ISO 4138:2012(E), 2012):
\[ \text{steering-wheel angle gradient} = \frac{\partial \delta_H}{\partial a_Y} \]  

(1)

A vehicle that follows a circular path at increasing speed generates centrifugal force on the vehicle that alters the turning circle and increases the lateral acceleration, \(a_Y\), away from the center of the turning circle. Consequently, the SWA, \(\delta_H\), is adjusted to maintain a circular path. The changes in SWA and lateral acceleration constitute the steering-wheel angle gradient expressed by Equation (1).

This equation is modified to account for two steering phenomena that affect path-following accuracy, namely, oversteer and understeer. Dividing Equation (1) by the steering ratio of the vehicle yields the understeer gradient (ISO 4138:2012(E), 2012):

\[ \text{understeer gradient} = \frac{\partial \delta_H}{\partial a_Y} \times \frac{1}{i_s} \]  

(2)

The steering wheel ratio, \(i_s\), for the game steering wheel is 1:1, and therefore Equation (2) reduces to Equation (1).

Understeer can occur when the radius of the circular path increases because of increasing lateral acceleration, \(a_Y\). Because empirical testing demonstrates that \(\delta_H\) and \(a_Y\) are positively associated, the driver should increase \(\delta_H\) in the direction of the turn to correct for understeer and to restore steady-state steering (Tandy et al., 2015). On the other hand, oversteer can occur when the radius of the circular path decreases because of decreasing lateral acceleration. Thus, \(\delta_H\) is decreased by the driver in accordance with Equation (2) to restore steady-state steering. Whereas Equation (2) applies to the game steering wheel, the understeer gradient is modified to apply to the sEMG-based interface. As the steering assistance system maintains a constant SWA during steady-state steering, the understeer gradient becomes (ISO 4138:2012(E), 2012):

\[ \text{understeer gradient} = l \times \frac{\partial \delta_H}{\partial a_Y} \]  

(3)

The understeer gradient is determined by the length of the vehicle, \(l\), lateral acceleration, \(a_Y\), and the radius of curvature, \(R\), of the circular path. Because empirical data typically indicate a negative association between \(1/R\) and \(a_Y\), a decrease in \(a_Y\) results in an increase in \(1/R\) and thus a decrease in \(R\) (Tandy et al., 2015). In the case of oversteer, the decrease in \(R\) can be mitigated by pressing the accelerator to increase lateral acceleration, \(a_Y\). As understeer increases \(R\), the driver corrects by releasing the accelerator or braking to decrease lateral acceleration. In summary, even though the steering wheel is held at a fixed angle, the driver could correct understeer and oversteer by longitudinally decelerating or accelerating the vehicle, respectively.

Based on transient and steady-state steering, a general strategy can be devised to maximize path-following accuracy for the driving scenarios (Figure 5). As mentioned previously in this section, there is a transient phase at the beginning of a turn involving the steering of the front road wheels to the Ackermann steer angle. When steady-state steering begins, the game steering wheel or, in the case of the sEMG-based interface, the accelerator can be adjusted to correct oversteer and understeer. Hence, the general strategy can be executed in the following sequence:

1. Maintain a constant low speed before and throughout the turn to prevent oversteer and understeer. This can be accomplished by constantly pressing the accelerator and not pressing the brake before and during the turn.
2. At the beginning of the turn, rotate the game steering wheel to 65° as soon as possible, or in the case of the sEMG-interface, supinate the right arm as soon as possible.
3. If oversteer should occur during the turn, rotate the steering wheel to the left, if applicable, or press the accelerator further.
4. If understeer should occur during the turn, rotate the steering wheel to the right, if applicable, or reduce accelerator depression. If the steering wheel is already rotated to the maximum SWA of 65°, understeer cannot be corrected with the steering wheel.
5. Do not return the vehicle to a longitudinal trajectory until the vehicle reaches the last road cone along the ideal circular trajectory.

Notice that item (1) in the above strategy is based on observations related to Equation (2), whereas item (2) is related to the previous discussion in this section regarding the minimization of the transient steering phase of a turn. Items (3) and (4) are based on observations regarding Equations (2) and (3). Finally, following item (5) maintains steady-state steering throughout the turn so that path-following accuracy can be maximized as mentioned previously in this section.

Items (1)-(5) were demonstrated through training videos for drivers who participated in experimental trials.

4.2 Experimental procedure

Experimental trials with the driving simulator were completed by a group of 24 healthy drivers, consisting of two females and 22 males. One test subject was left-handed and the rest were right-handed. The ages of test subjects ranged from 20 to 45 years, with an average age of 23. Thirteen test subjects had previous driving simulator experience. All test subjects had between six months and seven years of driving experience, and the test subjects all had standard driver’s licenses issued by the Government of Japan. The test subjects were recruited through referrals from colleagues at The University of Tokyo and by response to recruitment flyers that were posted on the university campuses. Ethical approval for this experiment was obtained from the ethics committee of the Interfaculty Initiative in Information Studies within the Graduate School of Interdisciplinary Information Studies at The University of Tokyo.

Test subjects completed driving scenarios with the sEMG-based HMI and the game steering wheel (Figure 5). Acceleration and braking of the car were performed with a set of pedals. A turning maneuver was completed only if the center of the front bumper of the car passed the first and last road cones along the turn without running into an island. Furthermore, the test subjects were instructed not to press the brake pedal until the car cleared the last road cone so that the execution of a turn would not be influenced by the operation of the brake pedal. However, releasing the accelerator was
allowed, as this operation was included in the strategy outlined in Section 4.1.

Operation of the sEMG-based HMI followed the steps shown in Figure 8. First, the accelerator was pressed to move the virtual car forward, and then the test subject supinated the right forearm to begin turning to the right. The test subject then supinated the right forearm again to exit the right turn before pressing the brake pedal to stop the virtual car. The same procedural structure was repeated with the game steering wheel in place of the sEMG-based HMI.

Throughout the execution of a right turn, the elbow of the test subject rested on a desk (Figure 8). This assisted with the maintenance of elbow flexion at 90° and flexion of the right arm at 90° from the anatomical position. When the virtual car was not turning, the surface of the palm of the right hand was held nearly parallel to the sagittal plane. Given that the virtual car was moving forward along a linear trajectory, supination of the right forearm steered the front road wheels of the virtual car to the rightward Ackermann steer angle. Supinating the forearm again returned the front wheels to their original positions so that the virtual car could continue moving forward along a linear trajectory.

Training of the test subjects involved the viewing of a slide presentation that included written interface operation instructions as well as videos of an expert user demonstrating the operation of each interface for each driving scenario. Test subjects who viewed the presentation went on to complete driving simulator training for the sEMG interface equipment, followed by driving simulator training for the game steering wheel. Training for a given interface consisted of the completion of driving scenarios in the following order: U-turn, 90° turn and 45° turn (Figure 5). Each scenario had to be successfully completed twice before a test subject could move on to the driving simulator trials for data collection.

Two simulated SWR settings for the sEMG-based HMI were used during the experimental trials to observe the effect SWR on path-following accuracy. Some commercially available steering motors could provide maximum SWRs that ranged from 720 to 1,300 deg/s (Forkenbrock and Elsasser, 2005). However, the driving simulator was only capable of providing a maximum simulated SWR of 720 deg/s. Given that all the driving scenarios were designed to require the SWA to transition between 0° and 65°, the transient steering phase was determined by dividing 65° by 720 deg/s to get 0.1 s. This was the transient phase of the fast-turning sEMG-based HMI. A considerably longer transient phase of 1 s for the slow-turning sEMG-based HMI was also tested to confirm an a priori observation derived from the discussion in Section 4.1 – that prolonging the transient phase reduces path-following accuracy. According to this observation, the fast-turning interface would be more accurate than the slow-turning interface. Furthermore, as previous driving simulator testing has shown that the transient phase for two-handed steering wheel rotation was 0.268 SD 0.065 s, the fast-turning interface would be more accurate than the game steering wheel, whereas the slow-turning interface would be less accurate (Pandis et al., 2015). Hence, it was anticipated that the experiment would confirm the following:

**H1.** For most of the tested driving scenarios, the slow-turning sEMG-based HMI has a lower path-following accuracy than the game steering wheel.

**H2.** For most of the tested driving scenarios, the fast-turning sEMG-based HMI has a higher path-following accuracy than the game steering wheel.
The experiment was structured to test these hypotheses by evenly dividing the test subjects into two groups, shown in Table I. Group A consisted of 12 test subjects who completed the three driving scenarios in Figure 5 with the game steering wheel and the fast-turning sEMG-based interface. Therefore, each member of Group A participated in a total of six experimental conditions that are listed as 1-6 in Table I. Conditions 1-3 were compared to conditions 4-6, respectively, to assess H2. Group B consisted of another 12 test subjects who followed the same procedure as Group A, but the slow-turning sEMG-based interface was used instead of the fast-turning counterpart. Each member of Group B participated in another set of six experimental conditions that are listed as 7-12 in Table I. Conditions 7-9 were compared to conditions 10-12, respectively, to assess H1.

Within-subject randomization for the conditions of Group A was carried out by dividing the group into two subgroups of six and applying a balanced $6 \times 6$ Latin square to each subgroup (Shuttleworth, 2009). The same randomization was applied to the conditions of Group B.

Each test subject was allowed five attempts per condition. Given that the sEMG-based HMIs fell under the category of sEMG interfaces and the game steering wheel fell under the category of steering wheel interfaces, the number of experimental trials was calculated as follows:

\[
3 \text{ driving scenarios} \times 5 \text{ attempts} \times 24 \text{ test subjects} \\
\times 2 \text{ interface categories} = 720 \text{ trials}
\]

As a means of reducing the risk of insufficient data from each test subject, only the first three successful attempts for each experimental condition were used for data analysis.

The shortest distance between the ideal trajectory and the edge of a given road cone in any attempted scenario was 1.1 m (Figure 5). The lateral error of the actual trajectory was calculated by finding the absolute value of the difference between 1.1 m and the shortest distance between the actual trajectory and the edge of the road cone. Because there are five cones per scenario, the lateral error was calculated five times for each trial. For each condition in Table I, the median lateral error was calculated across trials. The data spread about the median lateral error was expressed as the interquartile range (IQR) (Upton and Cook, 1996).

Data used to calculate path-following accuracy were also used to generate two-dimensional plots of the median trajectories for each interface. Data from Group A and Group B were used to plot the median trajectories for the fast- and slow-turning sEMG interfaces, respectively. The median trajectory for the game steering wheel was plotted from the data of both groups. Observations were made from the driving trajectories regarding the relation between the driving scenarios and path-following accuracy (Section 5).

Statistical significance tests were the criteria for confirming $H1$ and $H2$. Some data sets did not have a normal distribution as indicated by Shapiro–Wilk tests, where $p < 0.05$ (Shapiro and Wilk, 1965). Thus, the nonparametric Wilcoxon signed-rank test was used to calculate statistical significance with a significance level of $p < 0.05$ (Whitley and Ball, 2002). If there was a statistically significant difference in the sense that the game steering wheel had higher path-following accuracy than the slow-turning sEMG-based HMI for most of the tested driving scenarios, then $H1$ would be confirmed. Similarly, $H2$ would be confirmed if the fast-turning sEMG-based HMI had a lower median lateral error than the game steering wheel, and this difference was statistically significant for most of the tested driving scenarios. Even if $H2$ was not confirmed, the path-following accuracy of the steering assistance system would be validated if there was at least no statistically significant difference between the game steering wheel and the fast-turning sEMG-based interface.

### 5. Results and discussion

Based on data from the experimental trials, the path-following accuracy of a simulated automobile was calculated for a U-turn, 90° turn and 45° turn (Figure 5). Drivers in Group B used the game steering wheel and the slow-turning sEMG-based HMI to complete the scenarios (Table I). The results for Group B showed a statistically significant difference, namely, that the slow-turning sEMG-based HMI was significantly less accurate than the game steering wheel when performing a U-turn [Figure 9(b)]. There was no significant difference, however, in the case of the 90° and the 45° turns. Therefore, $H1$ was rejected because the sEMG-based HMI was comparable to the game steering wheel in most of the scenarios (Section 4.2).

Drivers in Group A completed the driving scenarios with the game steering wheel and the fast-turning sEMG-based HMI (Table I). The drivers steered with greater accuracy in all scenarios with the fast-turning sEMG-based HMI than with the game steering wheel [Figure 9(a)]. Because the U-turn was the only scenario where the difference between the interfaces was statistically significant, $H2$ was rejected (Section 4.2). Nevertheless, the fast-turning sEMG interface was at least comparable to the game steering wheel across all tested scenarios, and therefore the path-following accuracy of the fast-turning sEMG interface was validated.

Path-following accuracy varies between trials as indicated by the data summary in Table II. The IQR values for the slow-turning sEMG-based HMI are all higher than those of the other

<table>
<thead>
<tr>
<th>Test subject group</th>
<th>sEMG-based interface type</th>
<th>sEMG-based interface conditions</th>
<th>Game steering wheel conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>Fast-turning</td>
<td>Condition 1: U-turn</td>
<td>Condition 4: U-turn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 2: 90° turn</td>
<td>Condition 5: 90° turn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 3: 45° turn</td>
<td>Condition 6: 45° turn</td>
</tr>
<tr>
<td>Group B</td>
<td>Slow-turning</td>
<td>Condition 7: U-turn</td>
<td>Condition 10: U-turn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 8: 90° turn</td>
<td>Condition 11: 90° turn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 9: 45° turn</td>
<td>Condition 12: 45° turn</td>
</tr>
</tbody>
</table>
interfaces, meaning that the accuracy of the slow-turning sEMG-based HMI has the highest variability. In contrast to the other interfaces, the accuracy of the fast-turning sEMG-based HMI varies the least with IQRs that are consistently low across all scenarios. The fast-turning sEMG-based HMI is therefore associated with more repeatable path-following.

One pattern that is associated with all the interfaces, is the decrease in the median lateral error as the angle of the turning maneuver decreases from the U-turn angle to 45° (Table II). A possible reason for this pattern pertains to the median trajectories shown in Figure 10. The U-turn trajectories for all interfaces have the lowest error at the first road cone along the ideal trajectory because the longitudinal trajectory of the simulated car at the beginning of the scenario is enough to follow the ideal trajectory at the first road cone [Figure 10(a)]. A longitudinal trajectory of the virtual car provides the highest accuracy before reaching the third road cone in the 90° turn and before reaching the fourth road cone in the 45° turn [Figure 10(a) and (b)]. It is therefore expected that driving scenarios involving longer longitudinal trajectories are associated with higher path-following accuracy, as evidenced by Table II. In contrast, scenarios involving longer circular paths are associated with lower path-following accuracy. The median trajectories account for this lower accuracy by indicating that lateral error tends to progressively increase with the length of a turn. Notice that all the median trajectories terminate at the finish lines with lateral distances from the final road cones that are greater than the lateral distances from the initial road cones (Figure 10).

There are potential explanations for the lateral error in Table II. Although it may be a cause of lateral error, understeer does not explain why the median trajectory of the fast-turning sEMG interface tends to be the closest to the ideal trajectory, whereas the median trajectory of the slow-turning sEMG interface tends to be the farthest. Because these two interfaces only differ with respect to the duration of their transient steering phases (Section 4.1), perhaps there is a relation between transient steering phases and lateral errors. As opposed to the 1 s transient steering phase of the slow-turning sEMG interface, the fast-turning sEMG interface has a transient steering phase of 0.1 s. This shorter period allows steady-state steering to begin earlier in the turn, resulting in a median trajectory with higher path-following accuracy. As a previously tested steering wheel for a driving simulator has an intermediate transient time of 0.268 SD 0.065 s, the median trajectory of the game steering wheel in the current study would hypothetically have the second highest path-following accuracy (Pandis et al., 2015). This expectation is confirmed because the median trajectory with the second largest lateral distance from the ideal trajectory tends to belong to the game steering wheel (Figure 10).

Although Figure 10 shows that the median trajectories of the interfaces differ with respect to path-following accuracy, only the U-turn is associated with statistically significant differences between the interfaces (Figure 9). The U-turn thus appears to be the most effective of the simulated scenarios at distinguishing the path-following accuracy of the interfaces.

### Table II Summary of path-following accuracy data

<table>
<thead>
<tr>
<th>Test subject group</th>
<th>Interface type</th>
<th>Driving scenario</th>
<th>Median lateral error (m)</th>
<th>IQR (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>Fast-turning sEMG-based HMI</td>
<td>U-turn</td>
<td>0.55</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° turn</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° turn</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Game steering wheel</td>
<td>U-turn</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° turn</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° turn</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Group B</td>
<td>Slow-turning sEMG-based HMI</td>
<td>U-turn</td>
<td>1.1</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° turn</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° turn</td>
<td>0.2</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Game steering wheel</td>
<td>U-turn</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° turn</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° turn</td>
<td>0.4</td>
<td>1</td>
</tr>
</tbody>
</table>
6. Limitations

Given that the average age of the test subjects was 23 years, the results were relevant to regular driver’s license holders between the ages of 20 and 24 years, who comprised about 51 per cent of the nearly 9,000,000 regular driver’s license holders in Japan as of 2015[7]. Given that some age groups were not represented by the test subjects, the total population of regular driver’s license holders in Japan could have been more accurately represented by recruiting a group of test subjects with an age distribution that was close to that of the total population.

Two females and 22 males participated in the experimental trials. Based on data from a previous study that measured the range of motion and velocity of forearm supination, females supinated their left and right forearms 6-8 per cent faster than males, and therefore the results may not have accurately reflected biomechanical differences between males and females (Rahman et al., 2014). Because the inclusion of more female participants may decrease the median time to perform supinations, and consequently the total time to steer from a longitudinal trajectory to the turning circle may also decrease, it was expected that the median lateral error of the sEMG-based HMI would decrease, if not remain approximately the same. Thus, the results may have conservatively estimated the accuracy of the sEMG-based HMI.

Setting the SWR of the sEMG-based interface to a transient steering phase of 0.1 s resulted in more accurate U-turns than those of the game steering wheel. As the differences between these interfaces were only statistically significant for the U-turn, further studies that only adjust the SWR could include the U-turn as a driving scenario to observe any statistically significant differences in path-following accuracy. For example, U-turns could be executed to determine different accuracies for transient steering phases between 0.1 s and 1 s. Based on these accuracies, the relationship between path-following accuracy and transient steering phases would be quantified in further detail.

Given that the steering assistance system was validated with a fixed-base driving simulator, steering feedback in the form of lateral vehicle acceleration and other aspects of an actual vehicle environment were not simulated. Furthermore, unlike the virtual car in the driving simulator, actual cars had cornering compliances such as steering system deflections that alter the Ackermann steering angle (ISO 4138:2012(E), 2012). Nevertheless, the design optimization of actual automobile steering systems could minimize the effect of cornering compliances on the Ackermann steering angle, and therefore the results of the current study could closely approximate vehicles with optimized steering systems (Pauwelussen, 2015).

7. Conclusions

An sEMG controlled steering assistance interface with a maximized SWR of 720 deg/s was found to have path-following accuracy that was at least comparable to a game steering wheel. The validation of this accuracy was conducted with a driving simulator that enabled drivers to complete a U-turn, 90° turn and 45° turn. The median lateral errors of the game steering wheel and the sEMG-based HMI indicated that a faster SWR was associated with greater path-following accuracy. The difference in path-following accuracy between the interfaces was statistically significant in the case of the U-turn, with the sEMG-based HMI being more accurate. Thus, future studies could incorporate the U-turn as a means of distinguishing the accuracies of interfaces with varying SWRs.

Acceptable path-following accuracy warrants further development of the sEMG-based HMI for an actual automobile. In place of the wet electrode setup in the current study, a wireless electrode armband consisting of dry electrodes would be configured to provide comparable signal measurement accuracy (Hakonen et al., 2015). In contrast to wet electrodes, dry electrodes do not need conductive electrolyte gel at the skin-electrode interface, and thus drivers would not need to clean the gel after using the electrodes. Another potential improvement would be a vibration device in the wireless sEMG armband to indicate the state of the steering wheel. Other devices could be realized as well, including untested components that were previously proposed, e.g. sound notifications during manual takeover and a motorized steering wheel that can sense torque input from the driver.

Notes

1 https://pressroom.toyota.com/releases/2017-toyota-corolla-product-specs.download
References

Steering assistance interface
Edric John Cruz Nacpil et al.


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Design of hazardous materials transportation safety management system under the vehicle-infrastructure connected environment

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Abstract
Purpose – For the purpose of reducing the incidence of hazardous materials transport accident, eliminating the potential threats and ensuring their safety, aiming at the shortcomings in the process of current hazardous materials transportation management, this paper aims to construct the framework of hazardous materials transportation safety management system under the vehicle-infrastructure connected environment.

Design/methodology/approach – The system takes the intelligent connected vehicle as the main supporter, integrating GIS, GPS, eye location, GSM, networks and database technology.

Findings – By analyzing the transportation characteristics of hazardous materials, this system consists of five subsystems, which are vehicle and driver management subsystem, dangerous sources and hazardous materials management subsystem, route analysis and optimization subsystem, early warning and emergency rescue management subsystem, and basic information query subsystem.

Originality/value – Hazardous materials transportation safety management system includes omnibearing real-time monitoring, timely updating of system database, real-time generation and optimization of emergency rescue route. The system can reduce the transportation cost and improve the ability of accident prevention and emergency rescue of hazardous materials.

Keywords Hazardous materials, Transportation safety, Management system, GIS, Route optimization, Intelligent connected

Paper type Research paper

1. Introduction

With the rapid development of the economy and the accelerating process of industrialization, the demand for hazardous materials has been increasing year by year, resulting in a significant increase of traffic volume. Various types of vicious accidents have frequently occurred; therefore, all sectors of society have paid great attention to the safe transportation of hazardous materials. The special physical and chemical properties of hazardous materials can easily lead to secondary accidents when the accident occurred, resulting in dangerous goods leakage, explosion, poisoning and so on. According to statistics, in China, there are hundreds of security accidents caused by hazardous materials transportation every year (Lu, 2018). It has caused great losses and potential threats to the lives and property safety of the state and the people.

In August 1925, an electronic engineer of the United States Army Francis P. Houdina developed the first driverless car controlled by radio waves, which was officially unveiled in the USA. After that, intelligent connected technology has been rapidly developed worldwide, mainly used in the intelligent and networking of intelligent connected vehicle (ICV). In China, in the interpretation of “Made in China 2025” by the Ministry of Industry and Information Technology in 2015, the concept of ICV was first put forward, and the development goal was defined. ICV refers to the organic combination of vehicle...
networking and intelligent vehicle. It is equipped with advanced vehicle sensors, controllers, actuators and other devices, and integrates modern communication and network technology. They can realize intelligent information exchange, sharing and behavior coordination of cars and people, cars, roads, and backstage, and provide support for the driver’s driving behavior, so as to achieve a multi-vehicle system with safe, orderly and efficient running.

To regulate the transportation of hazardous materials, a number of laws and regulations have been issued on the safety management of hazardous materials transportation. However, there are still some problems, such as the lack of management techniques and the imperfect management system, etc. (Aini et al., 2001). For the transportation of hazardous materials, shippers and government departments lack a relatively complete transport safety and information management system, and the laws and regulations concerning the safety of hazardous materials transportation still need to be improved.

Since 1990s, many experts and scholars have carried out more systematic and in-depth study on the issues of. Information technology, risk assessment, mathematical statistics and optimization method have been widely used in the field of hazardous materials transportation safety management. Julian (1993) introduced the type of traffic and communication system established on the basis of the consensus by the European Energy Commission, he also described the European freight management department’s regulatory methods for the hazardous materials transportation. Fabiano et al. (2002) studied the framework for risk assessment and decision-making of hazardous materials transportation. Daniels and Daniels (2002) put forward the “integrated emergency management”, namely, “full risk, whole process” emergency management system. Subsequently, Emergency Management Institute (2003) has studied some problems of the integrated emergency management, such as all-hazards approach, integrated management system, life cycle management and unified allocation of materials. Kara and Verter (2004) theoretically designed the hazardous materials transportation network in Canada. Pasquale et al. (2005) proposed a remote real-time monitoring system for hazardous materials transportation. The system can diagnose the vehicle’s technical condition, operation risk and cargo defect in advance. From analyzing the causes of hazardous materials transportation accidents, Lian and Liu (2006) put forward an intelligent whole course transportation monitoring system based on GPS positioning. Tang and Yang (2007) analyzed the advantages and disadvantages of the hazardous materials transportation environment and Radio Frequency Identification (RFID) technologies, applied RFID to the hazardous materials transportation. Tao et al. (2007), from the hazardous materials road transportation emergency management status quo, built the overall framework of emergency transportation system of hazardous materials transportation. In accordance with the relevant steps of Intelligent Transport System (ITS) framework in China, Zhao et al. (2008) have designed the system framework of road hazardous materials transportation management information system based on ITS. Pietro et al. (2008) study the application of the problem framework approach to simulating the demand for hazardous materials transportation monitoring system. Fabio et al. (2009) proposed a real-time monitoring system of hazardous materials transport vehicles based on the wireless sensor networks, the system can synchronously check the position of the vehicle, the mechanical condition and cargo status. Romano and Romano (2009) developed a decision support system which can quantify the risk of hazardous materials transportation, it effectively reducing transportation risk, and providing reference for land planning and emergency management of relevant departments. Liu (2011) used system theory and system engineering methods combined with scenario construction to conceptualize the emergency plan system and discusses its overall structure, concept classification, and functional composition. Li (2013) established a theoretical framework for emergency preparedness planning based on targeting the ability to promote, and put forward the construction methods of unconventional emergency situations, emergency general task lists, and the list of target capabilities to deal with typical scenarios of unconventional emergencies. Shi (2014) established a comprehensive management system for road transportation safety of hazardous materials. The system can not only query and manage all laws, regulations, and standards related to road transportation of hazardous materials, but also search for hazardous materials list, as well as query and manage emergency rescue measures and typical accidents cases. Combined with the typical accident of hazardous materials road transportation, Wu (2015) analyzed the main problems existing in the supervision mechanism and emergency rescue system of hazardous materials road transportation in China, and put forward some countermeasures for constructing the basic information system of hazardous materials transportation safety supervision and perfecting the emergency rescue equipment system of hazardous materials road transportation. Ma et al. (2018) established a comprehensive risk assessment model based on accident probability and accident consequences to evaluate the risk of urban road hazardous materials transportation, which providing a basis for the adoption of prevention and control measures, reducing the probability of urban road hazardous materials transportation accidents and the loss caused by accidents. By summing up the current situation of hazardous materials transportation management in China, Huang (2018) put forward and established the standard system framework of road transport regulations for hazardous materials.

To avoid the occurrence of hazardous materials transportation accident as much as possible, to minimize the heavy losses caused by the hazardous materials transportation to the state and people. With the full cooperation of government departments, further improve the relevant laws and regulations, strengthen the supervision of hazardous materials transportation safety. Most of the existing research results are based on a certain angle of hazardous materials transportation and research. Some scholars have chosen different methods to build models to calculate and analyze certain indicators of hazardous materials transportation, such as risk assessment models and path optimization models. There are also scholars who study how to improve the safety of transportation or how to manage hazardous materials transportation information more efficiently. At present, most of the design for hazardous materials transportation management system was only a systematic research and design of one
aspect of hazardous materials or hazardous materials transportation. For example, hazardous materials information management system, hazardous materials transportation path optimization system, hazardous materials emergency rescue management system, etc. Therefore, based on the analysis of the existing hazardous materials transportation management system, combining intelligent connected technology, a comprehensive hazardous materials transportation safety management system under the vehicle-infrastructure connected environment is designed. ICV is closely related to vehicle networking and intelligent transportation system. The common progress and development of these technologies will greatly improve traffic safety. In addition to the basic information management, the system also integrates early warning and emergency rescue function modules and path optimization. The purpose is to provide more efficient management means for the hazardous materials transportation, and optimize the process of hazardous materials transportation management. At the same time, the system strengthening the dynamic monitoring of the link in the transportation process, effectively improving transportation safety management level, and promoting road hazardous materials transportation safety management mode from “passive processing” to “active prevention” (Ma et al., 2015).

From three aspects, system design, subsystem function design and introduction and conclusion and outlook, this paper describes the framework of hazardous materials transportation safety management system under the vehicle-infrastructure connected environment.

2. System design

Based the background of ICV technology, this paper designed a hazardous materials transportation safety management system under the vehicle-infrastructure connected environment. The core technologies of ICV include vehicle overall sensing technology, wireless communication technology, vehicle ad hoc network (VANET) technology, safety assistant driving technology, information fusion technology and data processing technology. The system uses C# as the development language, based on the Microsoft Visual Studio 2010 platform to introduce ArcGIS Engine, SQL Server 2008, and GPS plug-in development. Using the hierarchical design as shown in Table I, the system has the characteristics of high maintainability, easy code reuse and flexible expansion. Based on SQL Server 2008 + C# platform, the database management function of hazardous materials transportation route optimization system is developed, and the information management of drivers, vehicles, hazardous materials, transportation records and emergency plans is realized.

The hazardous materials transportation safety management system designed in this paper, through the analysis of hazardous materials and its transportation characteristics, and made further refinement and perfection on the basis of the existing hazardous materials transportation management system. This system learn the prominent and mature functional modules from existing systems, making up for the shortcomings of the existing hazardous materials transportation safety management system is not comprehensive, setting up a relatively perfect transportation safety management system in the background of the geographic information system. The system consists of five subsystems, and the detailed functional modules are shown in Figure 1.

3. Subsystem function design and introduction

3.1 Vehicle and driver management subsystem

The vehicle and driver management subsystem mainly realizes the monitoring and scheduling of vehicles, fatigue monitoring of drivers (Ma et al., 2015), vehicle communication system and alarm system. This subsystem combines the vehicle overall sensing technology, wireless communication technology, vehicle ad hoc network technology, safety assistant driving technology of ICV. It can better monitor and judge the vehicles and the traffic environment around them, as well as timely and continuous updating and interaction of information.

3.1.1 Vehicle monitoring and scheduling

In the process of hazardous materials transportation, the real-time state of the carrier is very important. This module uses GPS, GIS, wireless communication network, RFID technology, sensor technology, multimedia and other related techniques for basic positioning and monitoring of all controlled vehicle, and real-time continuously display the vehicle state information and scheduling information, such as vehicle operating speed, acceleration, vehicle routes, continuous driving time, braking pressure and related security information. In addition, the real-time safety monitoring of the vehicle operating state, acquisition of the related data in the vehicle operating process. The data can be saved to the vehicle information database, its working principle as shown in Figure 2.

3.1.2 Driver fatigue monitoring

The main function is to analyze the driver’s eyes movement video transmitted by the vehicle monitoring system through the vehicle alarm system, and then calculate the fatigue index of the driver.

Fatigue index is the function of the driver’s eyes closing time. Setting a threshold which corresponding to the driver’s eyes closing time. Once exceeded this threshold (time), the driver is determined to be fatigue driving. The alarm system will receive the alarm information from the vehicle monitoring system,
Figure 1  Framework of system function design

Figure 2  Principle of vehicle monitoring and dispatching
and the alarm information will also be alarm to the driver through the vehicle monitoring system, which can reduce the potential risk of fatigue driving. Here we set the threshold of fatigue index is 10 (corresponding to 4 s eyes closing). If the driver’s eyes closing time is more than 4 s, that is the fatigue index is more than 10, the driver is judged to be fatigue driving (Ma et al., 2015).

3.1.3 Vehicular communication system

The system uses the Socket communication technology to realize the real-time communication between the monitoring system and the GPS terminal, the design process is shown in Figure 3. This system realizes the real-time communication of a monitoring center and multi GPS; data transmission is so stable and efficient that can be a variety of information transmission like speech and action; cross platform data transmission and rapid mobilization of emergency rescue force after the accident.

Vehicle communication system includes a GPRS module, sent the location information and system control signal to the server through the communication network of China Mobile Company. At the same time, the system control information sent by the server is received, and the data communication among subsystems is completed. The real-time communication between the vehicle terminal and the server is carried out through the China Mobile GPRS network, and the real-time communication between the clients of the command center is carried out through the internal local area network or internet.

The system also includes the function of the car phone, mainly through the voice processing module to complete the voice communication between the command center and the vehicle terminal equipment.

3.1.4 Vehicle alarm system

Vehicle alarm system is divided into vehicle automatic alarm and driver active alarm. Vehicle automatic alarm is a series of alarm behavior which is real-time monitoring by the vehicle monitoring system to the controlled vehicle, such as over speed alarm and vehicle abnormal alarm. The alarm information will be real-time response to the driver, but also time back to the server. After that, the driver immediately handles the emergency and waits for the server to release the relevant decision, meanwhile execute the received instructions in time. The driver’s active alarm is usually in the case of traffic accident or the vehicle terminal system is damaged, moreover cannot communicate with the server in time. Therefore, the driver takes the initiative alarm to obtain the corresponding rescue.

3.2 Dangerous sources and hazardous materials management subsystem

The safety of dangerous sources and hazardous materials is the most important thing in the hazardous materials transportation. Hazardous materials have certain harmfulness, and will produce new potential hazards in transportation. Once an accident occurs, it will cause huge casualties and economic losses to the society.

In the process of hazardous materials transportation, a series of sensors, such as temperature, pressure and fireworks, are used to track and monitor the dynamic information of temperature, pressure and leakage of hazardous materials. The subsystem in addition to the real-time monitoring for the safety situation of hazardous materials in the transportation process, it monitors the safety status in real time of dangerous sources in relatively static existence. To reduce the losses of society, the corresponding remedial measures should be taken as soon as possible in the case of hazardous materials leakage, explosion or transportation accident.

3.3 Path analysis and optimization subsystem

Based on the analysis of hazardous materials road transportation characteristics, using ArcGIS to fuse the 6 kinds of multi-source information involved in the route optimization of hazardous materials transportation, selecting effective sections suitable for hazardous materials transportation. Then, the paper selects the three factors, including road transportation risk, sensitive target population and transportation time, and designs a hybrid algorithm to solve the optimal transportation path of hazardous materials. With the help of ArcGIS Engine + C# platform, database technology and Socket network technology to develop the of hazardous materials transportation route optimization system. The hazardous materials transport vehicles from the transport path optimization to the monitoring during the transportation, and emergency rescue path planning and comprehensive management after the accident occurred are realized.

3.3.1 Generation of optimal transportation path

3.3.1.1 Multi source information fusion. There are six kinds of multi-source information in the subsystem, including vector geographic information, key protected place information, population distribution information, vehicle location information, emergency resource information and road interruption information. With the strong data storage, data fusion and visualization functions of GIS, the subsystem comprehensive use of ArcGIS, Google Earth and database technology, storing the multi-source information in the form of attribute fields in the background. Then the road transportation were screened to determine the effective road for the hazardous materials transportation, they will provides a powerful data support for the path optimization.

3.3.1.2 The generation of optimal transportation path. There are four characteristics in road transportation of hazardous materials: first, hazardous materials have different transportation risks in different sections; second, hazardous materials in transit are dangerous sources of flow, and it is

![Figure 3 Network communication process](image-url)
necessary to serve the destination as soon as possible; third, hazardous materials transportation accident may have a significant impact on the surrounding personnel and the natural environment, especially the leakage of toxic gases, the explosion of flammable and explosive products; fourth, hazardous materials transportation accident has the characteristics of sudden, delay, long-term and social, even some accidents easily lead to a certain degree of panic.

Comprehensively considering the characteristics of the hazardous materials transportation, the hazardous materials transportation risk, sensitive target population and transportation time are selected as the attribute elements of effective sections, the calibration methods of each element are as follows.

1 Road transportation risk
Using the traditional transportation risk definition model, as shown in formula (1) (R. Bubbico et al., 2004).

\[
R_{ij}^{k} = l_{ij} \cdot p_{ij}^{k} \cdot M_{ij}^{k}
\]

where:
- \(R_{ij}^{k}\) = risk value produced by the dangerous goods K passing through the road section \(ij\);
- \(l_{ij}\) = length of the road section \(ij\);
- \(p_{ij}^{k}\) = probability produced by the accident of hazardous materials K passing through the road section \(ij\); and
- \(M_{ij}^{k}\) = loss caused by the accident of hazardous materials K.

2 The number of sensitive target population
Buffer analysis in GIS has powerful functions of map information space retrieval and comprehensive processing of information. It can accurately and visually measure the population distribution around the hazardous materials transportation section. Take hazardous materials transportation section as the essential factor, take hazardous materials leakage or explosion impact radius as a buffer zone to establish buffer. Computing the total population of facilities covered by the buffer (schools, hospitals, hotels, scenic spots), it is defined as the sensitive target population. Calculate the number of sensitive target population according to formula (2).

\[
Q_{ij}^{k} = \sum m_{r} \cdot pop_{r}
\]

where:
- \(Q_{ij}^{k}\) = sensitive target population of dangerous goods K through the road section \(ij\);
- \(m_{r}\) = total number of the place \(r\) in the buffer field; and
- \(pop_{r}\) = number of people at the place \(r\).

The subsystem takes the road network of Lanzhou city as an example, on the influence radius \(d_{ij} = 0.1km\) of hazardous materials transportation risk as the benchmark. It using ArcGIS on the road buffer analysis, demographic results of sensitive targets are obtained. Its spatial distribution is shown in Figure 4.

3 Transportation time
The transportation time can be calibrated according to the historical record returned by the GPS for installation of hazardous materials transportation vehicles. The traffic information center can also collect the road network and vehicle data through the road infrastructure, and deal with the relevant data in the environment of vehicle networking. Traffic flow data of each monitoring point and road network are obtained, and then the road transport time is calibrated by using the United States Federal Highway Administration function (BPR function).

\[
t_{ij} = t_{oij} \left[ 1 + \alpha \left( \frac{x_{ij}}{u_{ij}} \right)^{\beta} \right]
\]

where, \(t_{ij}\) is the impedance of the road section \(ij\); \(t_{oij}\) is the zero flow impedance of the road section \(ij\); \(u_{ij}\) is the traffic capacity of the road section \(ij\); \(x_{ij}\) is the road traffic flow; and \(\alpha\) and \(\beta\) are the blocking coefficients. Wang Shusheng,
Huang Wei and other scholars combined with China’s national conditions to improve the BPR function, improved coefficient \( \alpha = 0.5668, \beta = 1.443 \).

4 A hybrid algorithm for optimal transportation routing
Based on the combination of the above six kinds of information and the effective transportation section is determined, comprehensively considering the three elements of transportation risk, sensitive target population and transportation time. First, entropy method is used for information fusion. And then, the comprehensive impedance of road section is obtained. Finally, the Dijkstra algorithm is used to get the optimal transportation path. The algorithm flow chart is shown in Figure 5.

The specific operation process of solving the optimal transportation path is explained below:

- **Step1**: using the ArcMap + Google vector map, the multi-source information is stored in the form of attribute table, and carrying out the information fusion.
- **Step2**: after multi-source information fusion, take the road section as the factor and the hazardous materials influence scope as the bandwidth, uses the ArcGIS to make the buffer analysis.
- **Step3**: whether the buffer zone contains key protection sites (water, chemical plants, power facilities, military control areas), if included, determined road as invalid section, road impedance set to be infinite; otherwise, Step4.
- **Step4**: determine the road as effective section, and respectively calculate its transportation risk, sensitive target population, transportation time.
- **Step5**: using entropy method to fuse information and solve the impedance of road section;
- **Step6**: using Dijkstra algorithm to solve the optimal transportation path.

3.3.1.3 Path visualization. ArcGIS Engine is a GIS control based on component object model (COM) technology launched by Environmental Systems Research Institute Company after ArcGIS 9, it can realize the map browsing and editing function, spatial information query and data analysis and rendering functions. The system uses the ArcGIS Engine + C# component type two development platform to realize the visualization of the hazardous materials optimal transportation path.

3.3.2 Generation of emergency rescue path
The rescue of hazardous materials transportation often requires multi agency cooperation. After the accident, first, querying the types of hazardous materials through the basic information query subsystem. And then, selecting the emergency rescue plan through early warning and emergency rescue management subsystem, searching the corresponding rescue agencies, and providing emergency rescue path.

The generation of emergency rescue path, which is taking the transportation time as the road impedance, using Dijkstra algorithm to solve it. Through the interface programming of the map layer, the emergency rescue path is visualized, and the emergency rescue route navigation map is released to the rescue agency, achieving rapid rescue and minimizing the loss.

3.4 Early warning and emergency rescue management subsystem
Hazardous materials should not be underestimated whether in transportation or in static state. To minimize the serious consequences caused by hazardous materials, the emergency rescue management subsystem accordingly carries out the emergency rescue management of hazardous materials as an independent module. This subsystem combines the information fusion technology and data processing technology of the ICV. It can obtain the first-time data quickly and timely, under certain criteria, using computer technology to analyze and synthesize the multi-source information, accordingly produce complete, accurate and effective comprehensive information.

**Figure 5** Flow chart of hybrid algorithm for solving optimal transportation path
3.4.1 Real-time access to accident information
Facing the hazardous materials such a special type of freight transportation, we must always grasp the hazardous materials transportation status or the safety of dangerous sources. Real time acquisition of accident information is the real-time acquisition and transmission of information through the vehicle and driver management subsystem and dangerous sources and hazardous materials management subsystem. The vehicle and driver management subsystem real-time reflects the accident information to the server through real-time monitoring and alarm system, such as real-time vehicle location, vehicle status, driver status, etc.; the dangerous sources and hazardous materials subsystem can quickly and accurately return the current safety situation of hazardous materials through the real-time monitoring of hazardous materials.

3.4.2 Pollution area forecast
There are many kinds of hazardous materials, and most of them have different degrees of pollution. After the dangerous source accident or hazardous materials transportation accident, it is bound to cause serious destruction and pollution to the surrounding residents, environment and public facilities within the scope of the accident point as the center. Therefore, the pollution area forecast after the accident is also a key point to take effective rescue measures.

The influence area of hazardous materials transportation accident depends on the nature of the hazardous materials, environmental characteristics, weather, wind speed and so on. In this paper, Gauss plume model is used to simulate the contaminated area, the model formula (4) is:

\[
X(x, y, z, t, H) = \frac{Q}{2\pi u\sigma_y\sigma_z} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \times \left[ \exp\left(-\frac{1}{2} \frac{(z - H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2} \frac{(z + H)^2}{\sigma_z^2}\right) \right]
\]

where \(X\) is the value of pollutant concentration (\(\mu g/m^2\)); \(x\) is the distance to the wind direction (\(m\)); \(y\) is the crosswind distance (\(m\)); \(z\) is the target elevation (\(m\)); \(t\) is the time after the hazardous materials leaks (s); \(H\) is the pollution source altitude (\(m\)); \(Q\) is the release rate of hazardous materials (g/s); \(u\) is the wind speed (\(m/s\)); \(\sigma_y\) and \(\sigma_z\) are the diffusion parameters of Y direction and Z direction respectively.

3.4.3 Security early warning system
Based on the analysis of hazardous materials transportation vehicles safety monitoring, a safety warning module of hazardous materials transportation vehicle is designed by using sensor technology, communication technology, global positioning system and hardware in the loop simulation technology. Real time monitoring of hazardous materials transport vehicles safety parameters by vehicle monitoring system, such as the tank temperature, pressure, liquid level, vehicle speed and vehicle distance. The monitoring data are sent back to the existing Tianxingjian platform of transit vehicle management system, to realize data sharing and monitoring. Before the accident occurs, the safety parameters of the hazardous materials transportation vehicle can be perceived. When the accident occurs, the system sent out alarm in advance to remind the driver taking immediate measures to avoid the accident. At the same time, the Tianxingjian monitoring platform can also real-time query the vehicle’s driving state, including the location, speed information. Even if an accident occurs, it can also locate in time to carry out rescue and minimize the accident loss. This module’s innovation are effectively monitor the security risks of hazardous materials transportation vehicle’s inside and outside, automatic test a large amount of given data and effective simulation of tank cars road running.

According to the characteristics of different hazardous materials, different transportation vehicles and different transportation routes, the emergency rescue plan for all kinds of hazardous materials accidents is stored beforehand in the system database. According to the real-time accident information obtained by this module and the predicted pollution area size, the best emergency rescue plan is screened and implemented. In the specific implementation of the rescue process, the system will receive important rescue instructions from the command department at the server side. After the implementation, the system will improve the corresponding emergency rescue plan, to provide more rapid and efficient implementation of the rescue.

3.5 Basic information inquiry subsystem
The subsystem provides a series of information query interfaces for different users, and each subsystem stores the basic attribute information or records in the corresponding database while working. The transportation enterprise of hazardous materials, shipper, individual departments and driver families by verifying the validity and legitimacy, they can query the vehicle information, driver and escorts information, dangerous source and hazardous materials information, record information, rescue information and related documents in the scope of authority from the monitoring center database.

Interface programming of each data table in the hazardous materials transportation basic information management database according to the design principles of composite multiplexing. Taking the transportation record table as the core, the following table relations are connected with the personnel information table, the vehicle information table, the hazardous materials information table, the dangerous sources information table, the rescue information table and the related documents information table. The information increase, delete, change and check are realized through the encapsulation database operation class. The relationship between the data tables is shown in Figure 6.

3.5.1 Vehicle information query
One part of the vehicle information comes from the original database input to the basic information of the vehicle, another part is the real-time updating of the vehicle information in the database when the vehicle and driver management subsystem...
operates. The users who are allowed to query the information can query the vehicle type, brand, load, whether to get out of the car for transportation tasks, the current position and other relevant information.

3.5.2 Drivers and escorts information query
One part of the driver information from the basic information input of the original database, another part from the real-time update information on the driver vehicle and driver management subsystem, such as whether the driver is driving, physical status and other real-time information. The users who are allowed to query the driver’s information can query the driver’s name, sex, age, number, length of service, affiliation, contact, and whether to carry out transportation tasks and other relevant information. They can query escort related basic information like the driver’s.

3.5.3 Hazardous materials information inquiry
One part of the hazardous materials information from the basic information input of the original database, such as type, name, number of hazardous materials, and whether to participate in transportation operations, another part comes from the dangerous sources and hazardous materials management subsystem to update the real-time condition of hazardous materials, such as the increase and decrease of the quantity, the change of the hazardous materials status, etc. The users who are allowed to inquire the information can inquire about the latest situation of hazardous materials.

3.5.4 Dangerous sources information inquiry
The basic information of the dangerous sources include the name, type, nature, protection method, emergency treatment method and so on. All of this basic information is stored in the initial database. In addition, through the real-time monitoring of the dangerous sources and hazardous materials management subsystem, the real-time information of the dangerous sources will be updated, such as the change of the inventory of hazardous materials before and after the transportation task. According to the specific requirements of the relevant departments, the dangerous sources information open query permissions only for some users.

3.5.5 Transportation records query
Transportation records occurred after the transport operation, mainly include transport path generation in path analysis and optimization subsystem, real-time generation of transport paths and vehicle trajectory images by the vehicle monitoring and scheduling module in vehicle and driver management subsystem. Besides, transportation records include the relevant information of vehicles, drivers, escorts and hazardous materials in a transport operation. The users who are allowed to query this information can query transportation records or replay the vehicle running tracks and images.

3.5.6 Rescue information query
Rescue information is generated after the implementation of rescue operations, they are divided into three aspects: before the rescue, during the rescue and after the rescue. Rescue information includes historical accident information, specific rescue measures and the results after rescue. The users, who are allowed to query this information can query transportation records or replay the vehicle running tracks and images.

3.5.7 Related documents query
Related documents include the relevant laws and regulations on hazardous materials transportation, the responsibility of hazardous materials supervision department, the system use
and query permissions description etc. The users who are allowed to query the information can inquire about the relevant laws and regulations.

4. Conclusions and prospect

4.1 Conclusions

The combination of hazardous materials transportation safety management system under the vehicle-infrastructure connected environment and ICV technology, which can improve the efficiency and safety of hazardous materials transportation to a greater extent. The design of hazardous materials transportation safety management system is discussed in this paper, revolves around strengthening the management of hazardous materials transportation on roads, integrates information management, emergency rescue management, path optimization and other functional modules on the basis of predecessors. A dynamic route optimization model and geographic information system are integrated to build a more comprehensive safety management system for hazardous materials transportation. It not only includes the management of basic information such as goods, vehicles and drivers in the transportation of hazardous materials, but also strengthens the safety and efficiency of transportation. The system expanding the range of users for hazardous materials transportation management system, breaking the situation that the government or the owner of the goods company is supervised independently, realizing the mutual supervision between government and individual, and the information communication among different regions, departments and enterprises, making the transportation process of hazardous materials transparent. Before the accident, the monitoring system and the early warning system can provide timely warning information, and relevant departments or personnel take effective measures to avoid accidents. At the moment of the accident, the power and responsibility can be clearly defined, and the further development of the accident can be controlled at the first time, the occurrence of secondary accidents can be avoided. The path optimization system not only optimizes the normal transportation path, but also provides the emergency rescue path, which effectively improves the safety and efficiency of the hazardous materials transportation.

This paper theoretically perfects the incomplete areas of existing hazardous materials transportation management system, but also has some shortcomings. In addition to the subsystem involved in the paper, there are some basic functional modules not discussed in detail, such as vehicle navigation, vehicle registration, accident processing flow, etc.

4.2 Prospect

The particularity of hazardous materials transportation is unavoidable. Therefore, while designing and developing a perfect transportation management system, it is necessary to enhance the transportation safety capability of transport equipment. Nowadays, the intelligent driving assistant system, which is widely promoted in China, integrates location-aware technology. If it can be combined with hazardous materials transportation in the future, in addition to better coordinated vehicle-infrastructure control, unmanned driving is also a great breakthrough for the hazardous materials transportation. Integration of intelligent transportation and vehicle-borne information products is a better development direction for hazardous materials transportation industry. Intelligent connected has become an internationally recognized future development direction, which will greatly promote the development of hazardous materials transportation and the improvement of transport safety. To develop hazardous materials industry more safe and efficient, we should strive to establish a scientific, effective and well operated dynamic safety management system for hazardous materials road transportation. Combining the ICV technology, it can realize the efficient management of all kinds of information, dynamic and real-time supervision of the whole process of hazardous materials transportation. Furthermore, to strengthen the construction of emergency rescue management system, and provide effective cross departmental and trans regional supervision mode. To further optimize and perfect, the corresponding data should be obtained to evaluate the system on this basis. At the same time, the governments departments need to improve the relevant institution, strongly cooperate with enterprises to carry out safety management of hazardous materials transportation. Enterprises should also strengthen the training on all aspects of personnel quality, and actively promote the safety management of hazardous materials transportation, to provide more reliable security for the country and people.

References


Huang, P. (2018), Development of Management Information System for Hazardous Materials Road Transportation, Chang’an University, Belin.

**Design of hazardous materials**

Xuexyan Yang et al.


Further reading


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The research of traffic density extraction method under vehicular ad hoc network environment

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Abstract
Purpose – Traffic density is one of the most important parameters to consider in the traffic operation field. Owing to limited data sources, traditional methods cannot extract traffic density directly. In the vehicular ad hoc network (VANET) environment, the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interaction technologies create better conditions for collecting the whole time-space and refined traffic data, which provides a new approach to solving this problem.

Design/methodology/approach – On that basis, a real-time traffic density extraction method has been proposed, including lane density, segment density and network density. Meanwhile, using SUMO and OMNet++ as traffic simulator and network simulator, respectively, the Veins framework as middleware and the two-way coupling VANET simulation platform was constructed.

Findings – Based on the simulation platform, a simulated intersection in Shanghai was developed to investigate the adaptability of the model.

Originality/value – Most research studies use separate simulation methods, importing trace data obtained from the simulation software to the communication simulation software. In this paper, the tight coupling simulation method is applied. Using real-time data and history data, the research focuses on the establishment and validation of the traffic density extraction model.

Keywords Traffic density, VANET simulation, Vehicular ad hoc network

Paper type Technical paper

1. Introduction

There is an increasing need for traffic density estimation to improve the management-level transportation system. The dynamics of a traffic system can be typically expressed using three parameters – density, mean speed and traffic volume, until now, these data have been acquired by means of devices such as loop detectors, radars, magnetometers and television cameras.

While information from such devices is readily available, it is not sufficient to give us a lucid picture, as the coverage of these devices is limited in terms of the area that can be monitored; hence, the full scope and real-time traffic information cannot be obtained directly (Leduc, 2008; Marti et al., 2014). Therefore, as an ideal way of collecting traffic information, the traffic parameter estimation method based on the vehicular ad hoc network (VANET) technology has become a hot area of research.

Artimy (2007) proposed a local density estimation scheme, based on the relationship of average speed and density. The author derived an equation to calculate local density, which took into account the mobility pattern and the stopping time of the vehicles, but the simulation was not conducted in VANET environment. Panichpapiboon and Pattara-Atikom (2009) proposed a traffic density estimation method under the VANET environment, which was based on the number of vehicles that were close to the probe vehicle. In that method, the overall density was estimated according to the local density, and then the traffic density of the whole road could also be estimated.
research was extended to the clustering method afterward (Panichpapiboon and Pattara-Atikom, 2011), estimating the overall density based on the cluster member information, which was collected via the cluster head. However, that model is only applicable when the space headway of vehicles obeys the exponential distribution. Fogue et al. proposed real-time traffic density estimation method under the VANET environment by means of vehicle-to-vehicle (V2V) (Sanguesa et al., 2012), vehicle-to-infrastructure (V2I) (Sanguesa et al., 2012; Barrachina et al., 2015) and V2X (Barrachina et al., 2013) technology, which verifies that the regression models can estimate the traffic density of any given city precisely. On this foundation, Sanguesa et al. (2016) proposed an improved traffic density estimation method; the effect of the whole length of road network was considered. As the method mainly focused on the average traffic density of the whole road network, the traffic density of a certain segment was not considered. Arbibai and Weigle (2009) and Kernet (2009) proposed traffic parameters’ extraction method in the VANET environment. The traffic parameters, including the time mean speed, space mean speed, traffic volume and average travel time, can be extracted. The research has been further improved (Arbibai and Weigle, 2011), and a dynamic traffic monitoring system was designed under the VANET environment. The results show that the average speed and travel time can be estimated accurately even in a low penetration rate; however, the only situation in free flow has been considered, whereas the other traffic state, such as traffic jam, was not considered. In general, although there are some improvements in the acquisition of traffic density, the deficiencies are also apparent, which mainly reflected in the following aspects:

- **Data sources**: Some researchers only use the real data from traditional traffic environment, or the static data obtained from separated simulation, both of them cannot reflect the VANET information interaction environment.
- **Simulation method**: Most research studies use separate simulation methods, importing trace data obtained from the simulation software to the communication simulation software.
- **Model applicability**: Most relevant research studies consider only the traffic parameter acquisition in a free-flow environment, whereas the abnormal state, such as traffic jam, has not been considered.

Therefore, considering the deficiencies of the existing research studies, the tight coupling simulation method would be applied in this paper. Using real-time data and historical data, the research focuses on the establishment and validation of the traffic density extraction model.

The remainder of this paper is organized as follows. Section 2 describes the necessary assumptions and definitions of this research; Section 3 illustrates the traffic density extraction model; Section 4 expounds the construction of simulation platform; Section 5 discusses the simulation results; and finally, Section 6 provided the conclusions.

## 2. Question description and parameter definition

Traffic information of any vehicles can be extracted directly from the data package that the on-board unit (OBU) sends to the roadside unit (RSU). That provides good conditions for the estimation of traffic density of the lane level, section level or even the network level. To simplify the question, the study of this paper is carried out on the basis of the following assumptions:

- The Doppler effect caused by the high-speed OBU (vehicle) is not considered.
- Every OBU (vehicle) has the same RX sensitivity and the effective transmission range.
- Every OBU (vehicle) can get lane-level location information.
- The penetration rate of OBU (vehicle) is 100 per cent.
- The impact of different communication performances (package size, sending power, transmission frequency) on the extraction accuracy under the VANET environment is not considered.
- Assuming the RSU is installed in the middle of the segments, covering all the road network.
- The effect of Beacons-level package and MAC-level package is not considered, assuming the communication process is ideal.

**Definition 1**: Package – In the VANET environment, the package format of V2V and V2X communications is defined as follows.

In the packages, VID represents the unique identification of a vehicle, RID represents the unique road segment of which the vehicle is running in, Lane-ID represents the number of lanes in which the vehicles are located, and PosX and PosY represent x- and y-coordinates of the vehicles, respectively. Speed and Acc represent the real-time speed and acceleration of vehicles, respectively, and Vctype represents the type of vehicles.

**Definition 2**: Segment – From the RID information mentioned above, the detailed information of that segment can be acquired. Any segment can be expressed as the five-dimension group listed below:

\[ r = \{ s(x, y), e(x, y), V_{\text{max}}, n, \overrightarrow{D} \} \]

where \( s(x, y) \) and \( e(x, y) \) represent the beginning and ending coordinates of the segment, respectively; \( V_{\text{max}} \) represents the maximum speed of the segment; \( n \) represents the number of lanes; and \( \overrightarrow{D} \) represents the direction of the segment \( D \in \{ s \rightarrow e, e \rightarrow s \} \).

**Definition 3**: Vehicle type – From the Vctype information mentioned above, specific information of the vehicles can be acquired. In this research, three different vehicle types are defined: large-sized vehicle, middle-sized vehicle, small-sized vehicle, expressed as L, M, S, respectively. The characteristics and driving behavior of different vehicles are quite different. The unit conversion is needed when extracting traffic parameters. The vehicle conversion coefficient \( \omega \) and average vehicle length \( (m) \) are defined as follows:

\[
\begin{align*}
\omega &= \begin{cases} 
3.0, & \text{Vtype = L} \\
2.0, & \text{Vtype = M} \\
1.0, & \text{Vtype = S} \\
12, & \text{Vtype = L} \\
8, & \text{Vtype = M} \\
5, & \text{Vtype = S} 
\end{cases}
\end{align*}
\]

## 3. Extraction method of traffic density

Traffic density represents the intensive degree of a single lane, which can be explained as the number of vehicles per unit
length of the roadway (Kerner, 2009). This parameter is one of the most important parameters to consider in the traffic operation fields. Under the VANET environment, in high-penetration conditions (100 per cent OBU penetration rate), the communication of V2V and V2I is stable and reliable, so there are more possibilities of the extraction of traffic density. With the help of the abundance of the data sets under the VANET environment, a real-time traffic density extraction method has been proposed as follows.

In segment $i$, the instant number of vehicles $N_i(t)$ of lane $l$ at moment $t$ is equal to the vehicle ID number that RSU received between moment $r$ and moment $t_1$, that is:

$$N_i(t) = \sum (\text{uni}(\text{VID}) \times \omega)$$

In the packet Data (Vehicle), the following conditions must be met:

$$\begin{align*}
\text{RID} &= l \\
\text{LaneID} &= i
\end{align*}$$

(4)

In the two continuous moments, probably the RSU would receive multiple data packages sent by one vehicle, which is ascribed to signal frequency and road environment. To avoid the deviation caused by duplication statistics, assuming that the function $\text{uni}$ only represents the statistics of vehicle number that only possess a single VID.

Similarly, the number of vehicles $N_i(t)$ in the intersection at moment $t$ can be calculated as given in the following equation:

$$N_i(t) = \sum (\text{uni}(\text{VID}) \times \omega)$$

(5)

The number of vehicles of all the lanes in that segment at moment $t$ can be calculated as given in the following equation:

$$N_j(t) = \sum_{i=1}^{l-n} N_i(t) = \sum_{i=1}^{l-n} (\sum (\text{uni}(\text{VID}) \times \omega))$$

(6)

The instantaneous vehicle quantity of the whole road network at moment $t$ is equal to the summary of instantaneous vehicle quantity of the segments and intersections, that is:

$$N(t) = \sum_{l=1}^{l-m} N_j(t) = \sum_{l=1}^{l-m} \left( \sum_{i=1}^{l-n} N_i(t) \right)$$

(7)

$$= \sum_{l=1}^{l-m} \sum_{i=1}^{l-n} \sum (\text{uni}(\text{VID}) \times \omega) + \sum_{j=1}^{l-p} \sum (\text{uni}(\text{VID}) \times \omega)$$

In the equation, $m$ and $p$ represent the quantity of segments and intersections in the road network, respectively.

Therefore, the instantaneous density of lane $i$, segment $l$ and moment $t$ can be calculated according to the following equation:

$$k_i(t) = \frac{N_i(t)}{d_i} = \frac{\sum (\text{uni}(\text{VID}) \times \omega)}{d_i}$$

(8)

The instantaneous density of segment $l$ can be expressed as follows:

$$k_l(t) = \frac{N_l(t)}{d_l} = \frac{\sum_{i=1}^{l-n} (\text{uni}(\text{VID}) \times \omega)}{d_l}$$

(9)

The instantaneous density of the whole road network can be expressed as follows:

$$k(t) = \frac{N(t)}{L} = \frac{\sum_{i=1}^{l-n} \sum (\text{uni}(\text{VID}) \times \omega) + \sum_{j=1}^{l-p} \sum (\text{uni}(\text{VID}) \times \omega)}{\sum_{i=1}^{l-n} d_i}$$

(10)

In the equations above, $d_l$ represents the length of segment $l$, and $L$ represents the aggregation of all the segments in the road network.

4. Construction of simulation platform

4.1 Lane-change maneuver recognition

Based on the mature communication simulation and traffic simulation software, the mutually coupled simulation platform was constructed by means of the Veins frame; it can simulate the impact that communication has on road traffic. Meanwhile, the impact that road traffic has on communication is also available to this platform.

In the aspect of network simulation, OMNet++ was chosen as a network simulation software. It is a modular, component-based C++ simulation library and framework, primarily for building network simulators. Both C++ and NED are available for modeling. Different modules in OMNet++ are linked by ports, and the communication links are stored in NED files. Besides, OMNet++ has extensive GUI support, and owing to its modular architecture, the simulation kernel (and models) can be embedded easily into many applications (Varga and Hornig, 2008).

In the aspect of traffic simulation, simulation of urban mobility (SUMO) has been chosen as the traffic simulator. It is an open source, microscopic and multi-modal traffic simulation software. It allows simulating how a given traffic demand which consists of single vehicles moves through a given road network. Each vehicle is modeled explicitly, having its own route and moving individually through the network (Krajzewicz et al., 2012).

The Veins framework was selected to be the middleware that links network simulation and traffic simulation, in order to construct the mutually coupled VANET simulation platform (Segata et al., 2014). The communication module of the two simulators was extended by Veins, and then, the communication module interface of the traffic simulator can receive the instruction sent by OMNet++. Meanwhile, the execution of the next simulation step will be triggered, and the status of the vehicles node will also be sent to OMNet++. The overall structure of the simulation is as shown in Figure 1. It is mainly composed of middleware, traffic simulator and communication simulator. Furthermore, the map data and external application are also included. Limited to research contents, the specific external applications are not considered, and only the corresponding
interfaces have been reserved. In that platform, the network simulation software OMNet++ contains a physical layer, a MAC layer and an application layer, and it can also simulate the radio broadcasting effect. SUMO plays a role in traffic simulation, including real road network, vehicles’ mobility characteristics, operation rules in the intersection, etc. The Veins contains many submodules in the VANET environment, including obstacle submodule, scene submodule, node submodule, RSU submodule. When carrying out a simulation experiment, via TCP and Python script in Veins, OMNet++ and SUMO would be mutually and tightly coupled, and the execution command and vehicle trajectory information can also be exchanged.

This simulation platform was developed in the Windows environment; the software version information and hardware platform used in the paper are listed in Table I. In the platform, Python was used to develop the submodules of OMNet++, and JOSM was used to edit the road network information, which needs to be processed in the JAVA environment, and Notepad++ was used to edit the xml documents and configuration files.

4.2 Design of simulation procedure
The processing of the VANET platform is controlled by Veins. When simulation starts, the initialization stage would be entered first; SUMO and OMNet++ will be activated by a registered executable file; and the map data and OBU and RSU would be loaded successively. The communication and traffic environment would be created by configuration files. After the initialization stage, the simulation control stage would start, which is the key stage in the simulation process. Network simulation and traffic simulation would be carried out simultaneously. Network simulation would receive, synchronize and process traffic information, and it will

<table>
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determine whether to change the communication parameters. Traffic simulation would send traffic information, receive communication information and process the information to determine whether to change the traffic status. The detailed simulation procedure is as shown in Figure 2.

In the simulation process, the transitive relationship between information flow and traffic flow is as shown in Figure 3.

**4.3 Simulation scenario design**

In this paper, urban roads of Shanghai were chosen as simulation scenarios, which include complex road network and multiple signal-controlled intersections. Besides, considering the intensive buildings and trees by the roads, the communication conditions were much stricter than the urban expressway and highway. If the model can perform well in the
former environment, then it will also perform well in the latter one.

The simulated road network is in Pudong District, Shanghai, containing many complex environments, which include arterial roads (Zhangyang road), sub-arterial roads (Minsheng road), driveways and intersections. The actual road network is as shown in Figure 4. Using JOSM (Java OpenStreetMap) to consummate the map, the simulated road network transformed by SUMO is as shown in Figure 5. To simulate the impact that architectures and trees in an urban network have to package commissions, using the Polyconvert command in SUMO, based on the real conditions, the elements including buildings and trees have been added in a road network, which is expressed as colored polygons in Figure 5.

To avoid the effect of the accidental error, different random seeds are used to conduct simulation for five times. This would generate multiple simulation data sets, which can be used for validation. The simulation cycle length is 1,000 s (including 200-s system warm-up time), and the simulation time step is 100 ms, using the average value of each experiment containing five simulation times to do an analysis. In the simulation experiment, a scalar output file and a vector output file can be obtained. The scalar output file contains some statistical parameters of communication simulation and traffic simulation. It can be used to validate the mutual effect between traffic flow and information flow, whereas the vector output file contains many kinds of information such as time, location, speed and acceleration, which can be used to simulate the commission of data packages. Meanwhile, the traffic parameter extraction model can be validated based on them.

5. Simulation results analysis

When the OBU (vehicles) penetration rate reaches 100 per cent, theoretically, the traffic parameters, including accurate traffic density and space occupancy of vehicles, have no difference to the real value; therefore, in this section, only the practicability of the traffic parameters extraction method has been validated.

The intersection of arterial road “Zhangyang road” and branch road “ZhiYuanshen road” and four segments nearby have been chosen to conduct the simulation analysis, shown as the orange line in Figure 5. In that region, the Zhangyang road is bi-directional and has four lanes, and its segment length is 1,015 m. The Yuanshen road is bi-directional and has two lanes; the segment length is 912 m and the signal cycle length is 90 s. In the LOS C environment (stable traffic flow), simulating the ordinary traffic state and accidental traffic incidents, 740 million and 92 million data information were obtained, respectively. Before importing into MATLAB to extract traffic parameters, the text information in packages is required to be digitalized first, and the process is shown as follows:

For the “id” column, 0 represents west–east straight direction, 1 represents west–north left-turning direction, 2 represents west–south right-turning direction, 3 represents east–west straight direction, 4 represents east–south right-turning direction, 5 represents east–south left-turning direction, 6 represents south–north straight direction and 7 represents north–south straight direction. For the “type” column, the value below represents space headway of vehicles, 6.5 represents small vehicles, 10 represents middle vehicles and 14.5 represents large vehicles (Figure 6).

During the ordinary traffic state, taking the west segment of Zhangyang road (west —) as an example, the real-time traffic density of the whole segment is as shown in Figure 7. To be detailed, the density of different lanes is as shown in Figure 8. Lane-1 represents the rightmost lane and Lane-4 represents the leftmost lane. From the figure, it can be concluded that Lanes 1, 2, 3 presents cyclical fluctuation, the peaks of the wave are corresponding with red light, which means it is about to switch to green. While the valleys of wave mean it is about to switch to red. The fluctuation cycle is about 100 s, which is close to the signal cycle length (about 90 s).

These illustrate that traffic lights would probably lead to the intermittent activating and braking periodically to the stable traffic flow. When referred to the real-time density of the leftmost left-turn lane, the density shows small-scale fluctuations, but there is no evident periodicity; on the one hand, it is owing to the small amount of left-turn traffic demand. Further, it means the left-turn traffic light can meet the left-turn traffic demand. Additionally, the results also

Figure 4 Actual road network

Figure 5 Road network constructed by SUMO

Figure 6 Text information digitalization results
indicate that the real-time traffic density of different lanes is distributed quite unevenly. The leftmost lane shows minimum average density; meanwhile, the second left-turn lane reveals the maximum average density, which puts forward different requirements for traffic control. It is difficult to obtain the real-time traffic density of different lanes and the real-time lane-level traffic management and control under VANET environment by traditional methods.

As for the accidental traffic incidents environment, during the simulation process, the speed of a particular vehicle is set to be 0 km to simulate the occurrence of a traffic accident. From Figure 8, it can be observed that the traffic density of segments still presents periodic fluctuation, but the traffic accidents lead to an increase in segment traffic density. During 420s and 750s, the fluctuation of segments’ traffic density becomes much violent, and the peak of wave is higher when compared...
with the peak in ordinary traffic conditions, lasting about 330 s, which is a little longer than the simulation setting time (300s). This is because, the blocking flow caused by traffic accidents needs some time to dissipate. Moreover, this simulation experiment also shows that the precise real-time traffic parameter (less than 3-5 min) is of great importance to monitor the traffic accidents. In the actual applications, traditional traffic parameter acquisition device needs at least 5 min to upload the data, which is not able to be used in the monitor of short time traffic accidents (Figure 9).

6. Conclusion

The main contribution of this paper is the formulation of a traffic density extraction method under the VANET environment. This method represents a novel approach to extracting the vehicle density of lane level, segment level and network level, which overcome the disadvantages of the traditional methods. Meanwhile, based on the SUMO traffic simulator, the OMNet++ communication simulator and the Veins framework, a two-way coupled VANET simulation platform was constructed. Using the platform to validate the model, it has been verified that this model is pretty applicable to the complex traffic conditions.

In the real VANET environment, the data obtained would contain outlier data and missing data. Although random noise was added in the simulation process, there still exists a gap between actual data and simulation data. On this foundation, the following study should focus on increasing the authenticity of the data and enriching the variety of the extraction of traffic parameters.

References


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