Design and Implementation of Vehicle Automatic Emergency Pull over Strategy Using Active Safety Systems on a Driving Simulator

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ABSTRACT: This paper addresses a critical issue of automotive safety. Advanced Driver Assist Systems (ADAS) are getting enormous reputation with the increasing traffic on roads day by day. This paper presents a design of an Automatic Emergency Pullover (AEP) strategy using active safety systems for a semi-autonomous vehicle on a driving simulator. The idea of this system is that a moving vehicle equipped with an AEP system can automatically pull over on the roadside safety shoulder when the driver is considered incapable of driving. AEP requires supporting features such as Lane Keeping Assist (LKA), Blind Spot Monitoring (BSM), Vehicle and Pedestrian Automatic Emergency Braking (AEB), and Adaptive Cruise Control (ACC) for its execution. The design for application of AEP system has been explained along with its algorithm development and component structure. The implementation of AEP system has been explained along with its vehicle behavior and trajectory precision using software tools provided by Realtime Technologies, Inc. All major variables that influence the performance of vehicle after AEP activation, have been observed and remodeled according to control algorithms. The working of AEP system and its vehicle control strategy has been verified with the help of simulation results.

KEY WORDS: Safety, Scenario Designing, Active Safety, Subject Vehicle (SV), Automatic Lane Change, Adaptive Cruise Control, Pedestrian - Automatic Emergency Braking, Automatic Emergency Pullover, SimCreator, SimVista, Center of Gravity (CG). [C1]

1. Introduction

Around 1.24 million various road traffic accidents occur annually worldwide, which makes road traffic injuries the eighth leading factor for death and the prominent cause of death of young people aged between 15-29 years. 1)-2) These fatalities can be reduced with the help of intelligent vehicles safety systems. 3) Various vehicle active safety features have been developed in the past few decades namely: antilock braking, traction and vehicle stability control, lane keeping assist 4)-9), blind spot monitoring, automatic emergency braking, adaptive cruise control 7)-8) and more.

According to National Highway Transportation Safety Administration’s National Motor Vehicle Crash Causation Survey for automated vehicles, there are many reasons for the road accidents and there may be remedial ways to avoid them by using autonomous driving technologies. The report describes that a driver who is suffering from a heart attack or other physical impairment is unable to take full control of a partially automated vehicle. 2) Therefore, 2% of accidents are caused by some sort of physical impairment, such as a heart attack that inhibits driver’s ability to control the vehicle effectively. 2)-3, 5). In such a situation, a fully automated vehicle pullover will likely provide protection to the other traffic drivers.

The objective of this research is to design and implement the automatic emergency pullover (AEP) system algorithm that can prevent the potential collision in a scenario when the driver gets an impairment. AEP (Automatic Emergency Pullover) is an autonomous driving idea with limited scope – safely pull over without driver’s control. AEP can be combined with driver health monitoring system.

Automatic Emergency Pullover system can be implemented using many vehicle active safety technologies such as automatic emergency braking 11)-12), blind spot monitoring, and autonomous driving features such as adaptive cruise control and lane-keeping assist. AEP also requires some fundamental features in a driverless vehicle such as automatic lane change and autonomous mild braking. AEP need the capability of detecting the existence of adjacent lanes and shoulders. The rest of the paper is as follows: Section 2 describes the system concept for AEP. Section 3 explains the operation states and decision-making process in AEP. Section 4 provides the AEP control logic for simulation. Section 5 shows simulation results of three AEP operation examples. Section 6 concludes the paper.

2. AEP System Concept

AEP is defined as that a vehicle on the road can automatically switch from driver control to autonomous driving mode to pull over to the roadside safely when the driver is considered incapable of driving. There are many situations that cause driver incapable of driving such as: losing consciousness due to driver’s low glucose, heart fibrillation and so on. These unfortunate
conditions might happen anywhere during driving which could be fatal in busy traffic environments. The effective AEP needs a driver status monitoring system that can detect driver impairment and trigger the start of AEP. This paper only focuses on the operations after activation of AEP. Mechanism of AEP triggering is out of the scope of this paper.

Proposed AEP resembles a good human driver’s pullover approach. In an emergency situation, a typical driver will first turn the emergency lights ON, then try to pull over to the shoulder adjacent to the current lane. If there is no shoulder adjacent to the current lane, he/she keeps moving and tries to move to left or right lanes (one lane at a time) to get to a lane with the adjacent shoulder. The vehicle pulls over to the left side if there are fewer lanes to the left-hand side of the road. Otherwise, the vehicle pulls over to the right.

When AEP system is activated, the vehicle changes to full autonomous mode. The vehicle’s emergency lights will be turned ON along with flashing of front and tail lamps. A medical emergency phone call may be activated if the AEP is triggered due to health reasons. Then the AEP has to decide which side of the road it should pull over to and whether it is safe to pull over. Based on the surrounding environment information provided by the sensors, the AEP determines the control strategies and parameters for state operations.

In this paper, all the discussions related to left or right pull over are under the assumption that the road is located in right side drive countries (such as the US). The description can be mirrored to roads located in left side drive countries (such as Japan).

3. AEP Operations and Decision Making

The operation of AEP system mimics human driving behavior by the transition between states. The operation states include LKA_ACC, ALC_left, ALC_right, Pullover_left, Pullover_right, Braking (mild), Stop. Each state uses some well-known active safety features such as ACC, LKA, AEB, and BSM. These features are required because considering a scenario when the vehicle has to take a lane change maneuver and there is a traffic vehicle present in the adjacent lane. Further, considering a situation if a vehicle wants to pull over and there are objects present in the pullover shoulder. In both of these scenarios, BSM (Blind spot monitoring) plays an important role to take care of lane change maneuver during ALC. At the same time LKA and ACC help vehicle to keep it in the current lane for a short period of time until it is safe to make a lane change (either pullover lane or adjacent road lane). The AEP state diagram is shown in Fig. 1. Each block is a state. The arrows in between indicate the allowable state transition. State transition triggering events are indicated beside the transition arrows. During the AEP operation, the vehicle can only operate within the aforementioned set of operation modes. This set also covers all possible operation modes needed for AEP. The next question is how to switch among these operation modes correctly and ensure a safe pullover.

![State machine of the AEP system.](image)

3.1. Operation states in the AEP system

When the AEP is triggered, the default state is “LKA_ACC”. All operation transitions will begin from this state. During AEP operation, the vehicle is transitioned to “LKA_ACC” once each lane change is done. “LKA_ACC” describes the vehicle following behavior in the current lane by combining LKA and ACC systems. It acts as default vehicle operating state and stays in the state whenever it detects any potentially dangerous situation for pullover or lane change, such as busy traffic, the presence of obstacle or vehicle in the immediate adjacent lane. In this state, longitude speed is controlled and the vehicle stays in the same lane. The default ACC speed setting is the set point velocity on the current road.

“ALC_left” and “ALC_right” are automatic lane change maneuver to the left or the right side, respectively. This operation changes one lane at each time in multiple lane situations. During this operation, the vehicle still maintains the speed before lane
change but allows the speed adjustment for finding the opportunity to change to the adjacent lane.

“Pullover_left” and “Pullover_right” acts as the pullover maneuver of the vehicle to the shoulder or roadside. The vehicle can perform this operation only when it is at the leftmost/rightmost lane when there is a shoulder present on the left/right side. AEP in this state will first slow down gradually to a certain speed (e.g., 10 mph), then move to the shoulder lane, and then slowly brake to a complete stop. The vehicle keeps moving until it is on the shoulder completely. To realize this mode, both longitude and lateral speed control are considered. This operation mode can be completed only when the shoulder is clear for stopping.

“Braking (mild)” is the braking maneuver when the vehicle is in the rightmost lane and the right roadside pullover is not possible. It means that either there is an obstacle on the pullover lane or there is no shoulder. Braking is then the only safe choice for the vehicle rather than keep moving ahead to search for the shoulder. It should be noted that this operation is not allowed in any of the other lanes for overall road safety.

In this system, AEP operation mode can be triggered anytime during the AEP system operation when the AEB signal is received. Therefore, any pullover action can be interrupted and switch to AEB mode to ensure safety.

3.2. Switching events during the AEP operation states

There are many road variations and dynamic traffic conditions during AEP operation. The vehicle needs to switch to the proper states as mentioned in the previous section according to the traffic rules and safe practices. The AEP operation stays in the current state forever when there is not a transition triggering event to other states. The state change triggering condition is a combination of many factors including road condition and vehicle perception ability. Thus, the AEP system constantly monitors the road and traffic conditions and follows a decision-making process according to a decision tree as shown in Fig. 2 to determine the state transition related conditions. The shaded blocks are the state transition events generated from the decision tree. Note that the design of decision-making tree refers to the road system in North America. The default setting will be a pullover or stop at the right-hand side of the road.

After vehicle receives the AEP trigger during normal driving, the system will first determine whether the vehicle is in a single lane or multiple lanes road.

For the single lane road, the AEP first check if there are shoulders on left or right. Then the AEP checks if there are obstacles on either shoulder. The AEP generates the “Pullover to left” or “Pullover to right” signal when there is no obstacle on the shoulders. If there is no shoulder on both right and left or if the road is one way, the AEP system will then begin to check traffic density. The vehicle will keep on event “Stay in LKA and ACC” for not blocking the road if the road is either one way, or two ways but with high traffic density. Then the AEP continues the search for a safer pullover location until found one. On the other hand, when traffic is light, a state transition trigger to “Start braking” will be generated to switch to state “Braking (mild)”. In this case, vehicles behind can either stop or bypass the front vehicle by using lanes on opposite direction if there is one exist.

For multiple lanes road, the system will first determine which side to pull over by checking which side has fewer lanes. If there are fewer lanes on left than right, the vehicle will check if it sits on the leftmost lane. If it is not in the leftmost lane, the AEP system will initiate event “Change lane to left”, meaning vehicle will change one lane to the left. On the other hand, if the vehicle is in the leftmost lane, it will begin to check roadside situation to determine if it is safe to stop on the left shoulder. If a left shoulder is present and no obstacle on left shoulder, the vehicle will pull over to the left. Nonetheless, the roadside situation is changing dynamically during pullover. It could be possible that roadside shoulder becomes unavailable after the vehicle is in the pullover operation state. In this scenario, the vehicle should change lane to the right-hand side and check if there is any possibility to pull over on the other roadside. Therefore, the event of the vehicle, in this case, will be “Change lane to right”. The decision-making process is similar if there are less or equal lanes on right-hand side rather than left. The right-hand side branch of this decision-making tree is similar to the left-hand side and thus will not be repeated here. Note that, to avoid potential left-right oscillations of the system during a pull over, the vehicle will not move to the left-hand side lanes if it has already reached the rightmost lane. After each successful ALC, the AEP system goes back to “LKA_ACC” state and check for next lane change repeatedly until reaching to the side most lane.

For other state transition from “Pullover_left” and “Pullover_right” to “Stop”, the decision-making process is rather straightforward. For “Pullover_right”, if pullover is possible, the vehicle will stop on the shoulder. If pullover is impossible, the vehicle will switch its operation state to “Braking (mild)” and stop on the rightmost lane. For “Pullover_left”, if the shoulder is available and pullover is possible, the vehicle will stop on the shoulder. Otherwise, the state will change to “ALC_right” pairing with a left lane flag to avoid potential left-right oscillation. Flag value will be one if the vehicle is on the left-hand side of the road. Although the human driver can see the presence of shoulder on the right road edge, sensors may not be able to detect shoulder on the far side due to sensor range limitations. Therefore, a special decision-making method is included. Once it reaches the rightmost lane, flag value will be reset to default value zero.

Note that it could be possible that the road condition has changed and the vehicle is no longer moving in the leftmost/rightmost lane, such as lane numbers of road increased during vehicle pullover and now vehicle has to change lane to right or left. In this case, the vehicle should switch to “LKA_ACC” state and check for next pullover opportunity. In addition, the decision-making process can vary from vehicle to vehicle due to sensor range limitation mentioned previously.
4. AEP Control modules for simulation

To demonstrate the AEP idea, a driving simulation is developed. The structure of the simulation system is described in Fig. 3. The structure consists of human-in-loop driver model, vehicle model with various basic vehicle operation inputs, active safety system modules, and higher intelligent AEP system model. AEP system model consists of three control modules for the automatic determination of three major vehicle operation parameters, namely; velocity, braking, and steering.
4.1. AEP velocity control module

The AEP velocity control strategy is specified according to the AEP operating states.

- When the AEP is in “LKA_ACC” state, the AEP sets speed limit or the speed of the front vehicle as the vehicle ACC speed.
- When the AEP is in “ALC_right” or “ALC_left” state, the AEP adjust the vehicle speed to find a sufficiently long gap between the vehicles in the adjacent lane to be changed, and then slowly moves to the adjacent lane following speed of the front vehicle on the adjacent lane.
- When the AEP is in “Pullover_right” or “Pullover_left” operation state, the vehicle speed is reduced gradually until the vehicle reaches a slow velocity threshold (e.g., 20 mph), and then keep this vehicle speed until the vehicle complete the maneuver to the shoulder. Then the AEP brakes to a complete stop.
- When the AEP is in “Braking (mild)” state, the vehicle is controlled to brake to a full stop gradually.

4.2. AEP braking control module

AEP braking plays a critical role because of its significance in such a situation when the driver is incapable of control. When AEP is in “LKA_ACC” state, braking is for the purpose of ACC only. When AEP is in “Pullover_left”, “Pullover_right”, and “Braking (mild)” state, it provides a specific braking force for a particular threshold of velocity after receiving trigger signal, which helps in deceleration of the vehicle gently (Eq. (1)). When the vehicle reaches shoulder, and attain a slow velocity (e.g., 10 mph), AEP braking module provides a high magnitude of the braking force (e.g., 0.9 g), in order to bring the vehicle to a complete stop in roadside lane (typically high magnitude is applied just after the vehicle become straight in the roadside lane).

\[
\text{If } (\text{Velocity} > 10 \text{ mph}), \text{Brake} = 0.1 \text{ g}
\]  (1)

AEP braking also provides a high braking magnitude in the situation when there are obstacles on the shoulder to be pulled over.

4.3. AEP steering control module

AEP steering control module consists of four strategies for providing steering torque as follows. According to it if the vehicle is steering towards right lane or shoulder, steering towards left lane or shoulder, steering in the right shoulder, steering in the left shoulder.

“Right/left steering towards shoulder”, both provide steer torque according to a decision made after monitoring of current lane of the vehicle. It provides suitable steering magnitude in the appropriate direction of the roadside (either right or left).

In the simulation, lane numbers are mapped on the road for one directional traffic. Lane numbers are from left to right, 0 is left shoulder lane, 1 is leftmost lane, and then 2, 3, 4, ..., n, n is right shoulder lane and (n-1) is right most lane. Steering direction is provided using calculation from current vehicle lane number to pull over lane number by Eq. (2), (3), (4), (5).

For ‘n’ number of lanes:

For Odd:

\[
\text{If } \left( LN \leq \frac{1}{2} (n - 1) \right), \text{Towards left}
\]  (2)

\[
\text{If } \left( LN \geq \frac{1}{2} (n + 1) \right), \text{Towards right}
\]  (3)

For even:

\[
\text{If } \left( LN < \frac{1}{2} (n) \right), \text{Towards left}
\]  (4)

\[
\text{If } \left( LN \geq \frac{1}{2} (n) \right), \text{Towards right}
\]  (5)

where,

\(LN=\text{Vehicle Current Lane Number}\).

Distance to the obstacles in the shoulder or the pullover lane can also affect the steering torque. The steering will not be executed:

\[
\text{If } (\text{Distance to near obstacle} < 10\text{m}) \text{, and}
\]

\[
\text{If } (\text{Distance to next roadside object} < 25\text{m}),
\]

during the decision-making process.

After, getting into the roadside safety lane the “Right/left steering inside shoulder” strategy is used to make the vehicle aligned straight with the shoulder.

5. AEP Driving Simulation

To demonstrate the proposed AEP system, we developed a simulation platform on the RTI driving simulator using tools: SimVista and SimCreator (10). Typical simulation environment and behavior of the vehicle are shown in Figs 4 and 5. Fig. 4 shows the instance when the AEP was just triggered and Fig. 5 shows the instance when the vehicle just completed a safe pullover on the right shoulder.

Fig. 4 Simulation screen when AEP triggered.
Here, we describe results of three simulation cases for three scenarios.

- **Case 1**: Simple roadside pullover maneuver on the freeway without ambient traffic and without roadside objects.
- **Case 2**: Complex roadside pullover maneuver on the freeway with ambient traffic and with roadside objects.
- **Case 3**: Lane change roadside pullover maneuver without ambient traffic and with roadside objects.

For this simulation, we have considered “Lane Number” (i.e. \(n = 0, 1, 2, 3\)) as software defined lane numbers (Fig. 6).

Variables “Steer Torque” and “Heading Error” has typical behaviors mentioned below.

- Steer Torque (Nm): 0 means steer angle is zero, positive means steering left, negative means steering right.
- Heading Error (degrees): desired heading minus actual heading, positive means towards the right, negative means towards left.

### 5.1. Case 1 Maneuver

Fig. 7 shows a simple pull over to the right shoulder when there was no ambient traffic present and no obstacles present in pullover lane. Fig. 8 is the timing diagram showing the triggering time, the lane change time, and steering torque. The AEP was triggered at simulation time = 33s (Fig. 8). As soon as, the AEP system received a trigger signal, it executes pullover operation.

Fig. 8(a) shows the AEP triggering time, the vehicle steering torque corresponding to the scenario shown in Fig. 7. Intermittent spikes (green line) in the plot shows the behavior of steer torque until the center of gravity (CG) of the vehicle enters the shoulder (Lane 3) during simulation time 34s to 36s. Spikes represent that steer control module gives output every 0.2 seconds. As soon as the vehicle CG matches with the center of shoulder lane (Lane 3) at time = 39s, vehicle steer control provides sufficient steer torque to make vehicle straight and its Heading Error = 0 (time 39s to 41s).

Fig. 8(b) shows a plot for velocity and braking behavior in this simple pullover scenario. Here, the vehicle was doing pullover from Lane 2 to the shoulder (Lane 3). Originally, the vehicle velocity was 28 mph. After trigger, vehicle velocity started reducing with the help of braking control module (blue line). If the vehicle was not able to find obstacle free shoulder in 10m range, velocity control module kept the velocity at 20 mph (Red box), until vehicle CG entered the pullover shoulder lane. Instantly, after the vehicle entered Lane 3 (time = 36s) velocity control module disengaged. After vehicle reached the middle of shoulder lane and its velocity reduced to 10 mph (time = 39s approx.), braking control module provides high (0.9 g) magnitude to stop the vehicle completely.
5.2. Case 2 Maneuver

Fig. 9 represents a complex roadside pullover maneuver towards right side when there was ambient traffic present in the adjacent road lane and roadside objects present in the adjacent pullover lane. The vehicle was in Lane 2 and there was a shoulder (Lane 3). After the AEP was triggered at simulation time = 72 sec, the vehicle was not able to pull over because there were objects on the shoulder. Therefore, the vehicle kept moving forward until the shoulder was clear and then it will start to pull over.

Fig. 10 shows the timing diagram, the distance to the objects on the shoulder (pink line) can be seen. Since the distance to the object was less than the preset threshold of 10m and there was an object present ahead at a distance range of 25m, AEP keeps the vehicle moving in the current lane (time = 72.5s to 74s). Since there was a traffic vehicle present on the left, AEP kept the vehicle in the current lane (green line, time = 74s to 75s) and the velocity control kept the vehicle velocity to the set point through ACC approach similar to the one mentioned before. At the same time, AEP algorithm detects that the roadside object has been passed before passing of traffic vehicle (Eq. 6).

\[ \text{Traffic vehicle velocity} \approx \text{Subject vehicle velocity} - 5 \quad (6) \]

However, there was a roadside object present in the 10m vicinity but there was no object present in the headway distance of 25m now. In such a situation AEP algorithm decides to pull over towards adjacent pullover lane (Lane 3) on the right (time = 75s to 78s).

5.3. Case 3 Maneuver

In Fig. 11, a lane-changing scenario towards right roadside is represented when ambient traffic is not present on adjacent road lane in the specified sensor detection range but roadside objects are present in the adjacent pullover left side lane. Here, the vehicle has to make a lane change in the middle (one at a time) to get to the pullover lane on the other side.

Fig. 12 shows the timing diagram, AEP was triggered at simulation time = 398 sec and starts a lane change pullover maneuver. Due to detection of roadside objects on the left adjacent pullover lane (Lane 0) in the vicinity of 10m and headway distance of 25m (pink line and black line), the AEP decided to pull over to the right side. Therefore, velocity control kept the vehicle velocity at set point throughout the maneuver until it reaches the right most lane. It takes ALC maneuver from Lane 1 to Lane 2 (time = 398.5s to 399.5s). Then the vehicle straightens itself in Lane 2 (rightmost lane, green line, time = 399.5s to 400.5s). On the rightmost lane (Lane 2) AEP detects objects in the shoulder (Lane 3) and as no objects were detected.
on the shoulder, the vehicle moves to the shoulder (Lane 3), with the help of steer torque control (green line, time = 400.5s to 401.5s). Finally, steering control module provides sufficient torque to make the vehicle straight in this lane.

Fig. 11 Lane change pullover maneuver (right side).

If the trigger is a false alarm from the health device due to its malfunction, the driver has a button in his/her hand to reverse back the trigger and take control of the vehicle.

6. Conclusion

This research work discusses decision-making algorithm for the AEP system. The AEP utilize the active safety features such as lane keeping assist, blind spot monitoring, vehicle, and pedestrian automatic emergency braking, automatic lane change, and adaptive cruise control. A verification demonstration was developed using software tools provided by Realtime Technologies, Inc. The major benefit is that a driving simulator environment provides the freedom where new system development and behavior can be observed without significant cost.

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