

Fuzzy Automated Braking System for Collision Prevention

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Abstract

Many automobile accidents could be avoided if the correct amount of brake pressure had been applied at the proper time. In this paper we propose the use of a fuzzy control system that could be embedded in an automobile to remove the driver's reaction time from the situation. The system, consisting of two fuzzy controllers connected in cascade, analyzes possible accident situations based on the vehicle separation distance, their relative velocity and a static friction coefficient that represents the road conditions. The controller determines the sufficient brake pressure required to prevent collisions while providing a smooth ride for the vehicle's passengers. This smooth performance was achieved by using genetic algorithms to tune the fuzzy controllers' parameters.

I. PROBLEM DESCRIPTION

Objective

The purpose of our work is to design a fuzzy controller to automate and optimize the application of brake pressure to an automobile's brakes. The starting assumption is that two automobiles are moving in the same direction on a flat road. Their dynamics are defined by a set of initial conditions that specify the cars separation distance, their relative velocities, and the static friction coefficient reflecting the tire-road interface. The fuzzy controller must apply brake pressure to prevent a collision, while at the same time providing a smooth ride for the passengers. The first requirement implies that the two vehicles should never have any physical contact, while the second one implies that the brakes should be used only in the amount necessary, e.g., they should not undergo large excursions (such as 100% pressure) to make small adjustments.

In the standard scenario, the automobile in front (the "tracked" vehicle) will decelerate, and so the automobile behind (the "tracking" vehicle) must decelerate as well to avoid a collision. The fuzzy controller is responsible for applying brake pressure to the tracking vehicle dependent upon the deceleration of the tracked vehicle, which is used as a reference and hence *is not under control*. Another potential scenario that the system must handle is when the tracked vehicle is traveling at a slower initial velocity than the tracking vehicle. The tracking vehicle must automatically decelerate to match the velocity of the tracked vehicle and avoid a collision.

Motivation

Countless "rear-ending" automobile accidents could have been prevented or at least reduced in damage cost if the rear-ending driver had applied a sufficient amount of brake pressure at the right time. Unfortunately, the time required by the driver to understand potential accident situations, compounded with his/her delayed reaction times in applying the brakes, usually cause a lag between the identification of a potential accident situation and the execution of the corrective actions that will prevent the accident. By automating the task of assessing the situation and deciding the correct amount of brake pressure, we could prevent numerous accidents. This would significantly

decrease the amount of property and monetary loss due to accident damage, and it could save lives.

Solution Specification

The rate to which the tracking car will have to decelerate to avoid colliding with the tracked vehicle depends on many factors. For our study we considered the following three state variables: 1) separation between the two vehicles; 2) differences in their velocities; and 3) surface conditions (i.e., the friction coefficient between the vehicle tires and the road).

The solution developed is based on two fuzzy controllers connected in cascade. The first fuzzy controller generates the percentage of brake pressure that should be applied under *ideal* conditions. This value is based on the separation distance between the two vehicles and their difference in velocity. For example, if the vehicles are reasonably close together and the tracked vehicle is traveling much slower than the tracking vehicle, then we will have to resort to a large amount of brake pressure to prevent a collision. Likewise, if the two vehicles are far apart and there is only a small difference in their velocities, then a gentle brake pressure will result in a sufficient decrease in the speed of the tracking vehicle to prevent a collision. The second controller, connected in cascade, is then responsible for modifying this input by *taking into account the road surface conditions*, which are represented by a static friction coefficient, the controller's second input. The output of this second controller is the modified percentage of brake pressure that accounts for the *actual* road conditions.

Performance & Validation Criteria and Scope

The sensor technology required to measure the state variables used by the proposed system (range, relative velocity, and friction coefficient) is readily available. Laser range finders, and Doppler radars could provide the first two measurements, while wheel-slip sensors currently used for automobile Traction Control Systems or Anti-lock Breaking Systems (ABS) could estimate the third state variable. The required actuators are already installed in all automobiles equipped with ABS. Thus, we will limit the scope of our discussion to the core of the braking system, i.e., the intelligent control module. This control module could be used in a real-time system to calculate brake pressure in fractions of a second. By compiling the knowledge bases of the fuzzy controllers we will be able to implement the control module on existing on-board microprocessors [1-2].

For each of the seven test cases used to evaluate the controllers, we assume that the tracked vehicle will come to a complete stop and we expect that the subject vehicle will also come to a complete stop to avoid a collision. Once both vehicles have stopped there should be a final *separation distance of three meters*. We will consider a successful execution of the controller when the tracking vehicle will come to a complete stop at a distance of approximately three meters (+/- 0.5 m) from the tracked vehicle. If the tracking vehicle stops at a separation distance between zero and 2.5 meters, we will still

consider it a successful braking event, without however meeting the psychological comfort criterion. If the separation distance reaches zero, then an accident will occur and the goal of avoiding a collision failed. Under certain circumstances collisions are unavoidable. Under such conditions, the automatic braking should still attempt to minimize the tracking vehicle's velocity, reduce the momentum, and minimize the overall damage resulting from the collision. Table I shows an evaluation function that captures the above criteria.

II. RELATED WORK

In US Patent 5634698, Cao et al designed a "System for Controlling Brake Pressure Based on Fuzzy Logic Using Steering Angle and Yaw Speed" [3]. Cao's system is similar to the goals of the second controller—it measures the wheel slip and then uses fuzzy logic to determine how much brake pressure to apply to an antilock braking system. This system is focused on reducing vehicle skidding rather than on reducing the vehicle speed to prevent collisions. In US Patent 5416709, Yeh et al. designed a "Fuzzy Controller for Anti-Skid Brake Systems" [4]. This system, similar to Cao's, is only vaguely similar to the goal of the second fuzzy controller designed. Neither of these patented systems is sufficiently similar to the goal of this work to warrant a solution comparison or trade-off analysis. However, these patents are useful resources for identifying and understanding past applications of fuzzy logic in controlling automobile brake pressure.

III. SOLUTION DESCRIPTION

Model and Controller Assumptions

1. The two vehicles are traveling in a straight line, on a smooth surface with no gradient (i.e., a flat, leveled surface).
2. The tracking vehicle's brakes have ABS (Antilock Braking System) or similar mechanism, ensuring that the wheels will not lock during breaking situations. This assumption limits the simulation to consider only static friction
3. The application of brake pressure is linearly correlated with the deceleration the vehicle experiences, e.g., if 25% of the maximum brake pressure is applied, then the vehicle will decelerate by 25% of its maximum possible deceleration.
4. The variables used as inputs for the controller are available from on-board sensors.

Simulator Design

To develop the simulator, we solved standard physics equations to obtain the maximum potential deceleration exhibited by a vehicle based on its current velocity and the static friction coefficient between its tires and the ground. The output of the fuzzy controller (percentage of brake pressure to apply) is taken and multiplied by the maximum deceleration possible to obtain the actual vehicle deceleration. This actual deceleration is used to calculate the new velocity of the tracking vehicle one-second later. By knowing the original distance between the two vehicles and the instantaneous velocities of each, we can recalculate the new separation distance between the two vehicles. The following equations were used for the simulation:

$$d = \frac{V_o + V_f}{2} t \quad (1)$$

$$V_f = V_o + a\Delta t \quad (2)$$

Since we are attempting to find the maximum deceleration to

point of rest ($V_f = 0$), equations (1) and (2) can be combined to solve for the deceleration based on the initial velocity ' V_o ' and the minimum stopping distance ' d ' that must be traveled to come to a complete stop:

$$a = \frac{-V_o^2}{2d} \quad (3)$$

Note that this equation could have just as easily been derived using the standard formula $V_f^2 = V_o^2 + 2ad$.

By using equation (3), we can calculate the maximum deceleration possible. However, first we must know the minimum distance over which the car needs to stop. We can again use standard physics equations to determine this minimum stopping distance:

$$\text{momentum} = \frac{1}{2} mV^2 \quad \text{Work}_{\text{friction}} = -\mu mgd$$

By the work-energy principle, the change in momentum must equal the net amount of work performed in the system:

$$\begin{aligned} \text{Work}_{\text{net}} &= \Delta \text{Momentum} \\ \text{Work}_{\text{friction}} &= \frac{1}{2} mV_f^2 - \frac{1}{2} mV_o^2 \\ -\mu mgd &= -\frac{1}{2} mV_o^2 \end{aligned}$$

From the above equation we obtain:

$$d_{\text{stopping}} = \frac{V_o^2}{2\mu g} \quad (4)$$

First we use equation (4) to solve for the minimum stopping distance ' d '. Then we can use equation (3) to calculate the maximum deceleration that the tracking vehicle can experience. To solve for the new velocity of the vehicle after braking we take a percentage of this maximum possible deceleration and solve for the new velocity based on equation (2), with $\Delta t = 1$ second. For the simulation we assume that the amount of deceleration experienced is equal to the maximum possible deceleration multiplied by the percentage of brake pressure to apply (as generated by the fuzzy controller), resulting in:

$$V(t+1) = V(t) + (a_{\text{maximum}} * \% \text{Braking}) \Delta t \quad (5)$$

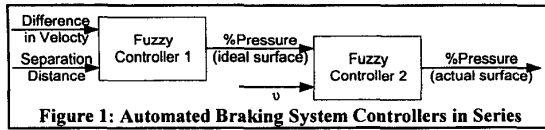
$$d_{\text{separation}}(t+1) = d_{\text{separation}}(t) + (V_{\text{tracked}}(t+1) - V_{\text{tracking}}(t+1)) \Delta t \quad (6)$$

Controller Design

To determine the amount of brake pressure to apply in the simulations, we designed two fuzzy controllers connected in series. The first controller uses the *difference in velocity* between the two vehicles (in km/h) and the *separation distance* between the two cars (in meters) to determine how much brake pressure should be applied. The second controller takes as input the desired brake pressure under ideal road conditions (i.e., the output of the first controller) and the *static friction coefficient* between the tires and the ground. From these inputs the controller determines the amount of brake pressure that needs to be applied to get the desired deceleration, taking into account actual road conditions. Note that the second controller cannot generate smaller amounts of brake pressure than its input (i.e., the value generated by the first controller, which assumes ideal road conditions.) Since the actual road will never be better than ideal, the second controller can only maintain or increase the braking pressure.

Architecture

Figure 1 shows an architectural diagram of the system.



Each fuzzy controller has an associated Knowledge Base (KB), containing scaling factors, term sets, and rule sets. In our experiments the scaling factors were incorporated directly into the range of each term set, leaving us with only two design choices: a structural model description (rule sets) and a parametric model description (term sets). We focused our tuning efforts on the term sets, as they tend to have a stronger impact on the controller's output. First, we initialized the controllers with uniformly spread term sets and with the rules sets illustrated in Table II and III. Then, we used Genetic Algorithms to fine-tune the term sets as illustrated in Figure 2.

GA Based Tuning of Fuzzy Controllers

We used the GA Banda package Version 8.1 [5] with the following settings: *Encoding = real-valued; Pop. size = 200; Prob. Mutation = 0.5 %; Prob. Repair = 1%; Prob. Crossover = 30%; Elitist strategy = YES; Crossover type = single cut; Maximum number generations = 2,000; Selection type = Rank.*

Each individual in the GA population represented a term set for the two fuzzy controllers. Each term set was defined by the core of the two extreme values and by the intersection points among adjacent slopes. The support of the previous term in the term set was then anchored to the core of the next term, thus guaranteeing that for each point in the universe of discourse the sum of its associated membership values would be equal to one. This encoding schema accomplished two functions: it reduced the degrees of freedom, i.e. the dimensionality of the search space, and it preserved a good property of the term set, which usually provides good interpolation behavior. For each instance of the term sets (i.e. for each individual in the population of a given generation) we ran the fuzzy controller and the dynamic simulator from seven sets of initial conditions, each defining different values of initial separation distance (ranging from 15 to 100 meters), cars velocities (ranging from 60 to 80 km/h), and road conditions (with the friction coefficient varying from 0.3 to 0.7). For each simulation run we used the same evaluation function, defined by Table 1. The first element in the table indicates the final separation between the tracking and tracked vehicles (in meters), while the second

element indicates the corresponding reward. The evaluation function shows that the ideal separation is centered at 3 meters. Negative distances indicate collisions and are highly penalized. Excessively long positive distances are also discouraged. The overall fitness of an individual is the sum of the evaluation functions over the seven initial conditions.

TABLE I: REWARD FOR FINAL SEPARATION (FITNESS FUNCTION)

Final Distance	≤ -10	$(-10, -7.5]$	$(-7.5, -5]$	$(-5, -2]$	$(-2, 0]$	$(0, 1]$
Reward	-25	-20	-15	-10	-5	5
	$(1, 2.5]$	$(2.5, 3.5]$	$(3.5, 5]$	$(5, 7]$	$(7, 10]$	$(10, 12]$
	8	15	10	5	2	-2

Result of Tuning

After completing the GA-based tuning, we obtained the final term sets for the two controllers, shown in Figures 3 through 6 below. The term sets in Figures 3 and 4 are used to evaluate the Left Hand Side (LHS) of the rules in Fuzzy Controller 1 (see Figure 1). The term set in Figure 6 shows the output of this first controller. The term sets in Figures 5 and 6 are used to evaluate the LHS in Fuzzy Controller 2 (Figure 1). This second controller also uses the term set in Figure 6. Note that we define the difference in velocity to be:

$$dV = V_{\text{tracked}}(t) - V_{\text{tracking}}(t) \quad (7)$$

The difference in velocity term set in Figure 3 has no terms for a difference in velocity less than zero. If the difference 'dV' is negative, then the tracked vehicle is moving at a higher velocity than the tracking vehicle and no deceleration is necessary. The separation distance term set in Figure 4 also has no terms for a negative separation distance. This is for a different reason: if the separation distance is zero or negative, then a collision has already occurred and applying brake pressure becomes moot. Though trained by the genetic algorithm, the friction coefficient term set in Figure 5 has a strong correlation to known friction coefficient values for various surface conditions—validating the GA's output. The typical coefficients of friction, as per Forensic Dynamics, Inc, [6] are: 0.8 = Dry Concrete; 0.7 = Dry Asphalt; 0.55 = Wet Concrete; 0.55 = Wet Asphalt; 0.3 = Snow; 0.15 = Ice. The final rule sets used for each controller can be seen in Tables II and III below. The rule sets exhibit symmetry around their main diagonals similar to the structure of the traditional Fuzzy PI controllers. The term sets and the rule sets define the structure and parameters of the fuzzy

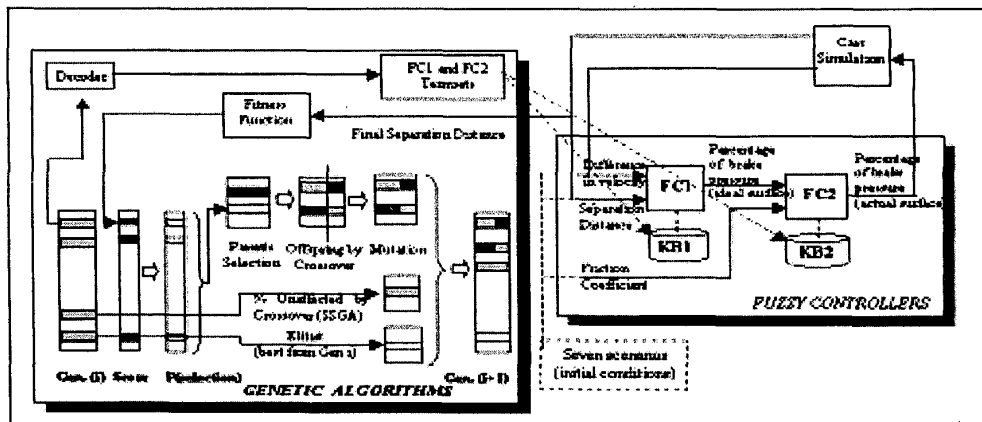


Figure 2: GA based Tuning of Fuzzy Controllers

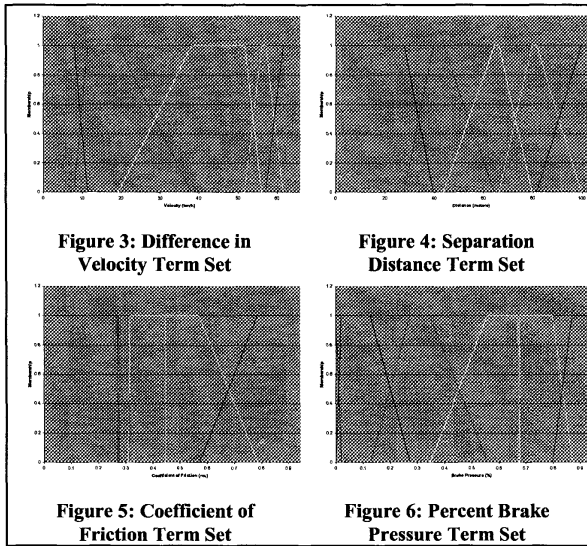


TABLE II: RULE SET FOR FUZZY CONTROLLER 1

		Separation Distance Term Set					
		VL _s	L _s	M _s	H _s	VH _s	
Δ Velocity Set	VL _{dv}	M _{50P}		VL _{50P}	Z _{50P}	Z _{50P}	
	L _{dv}	H _{50P}	M _{50P}		VL _{50P}	Z _{50P}	
	M _{dv}	VH _{50P}	H _{50P}	M _{50P}		VL _{50P}	
	H _{dv}	F _{50P}	VH _{50P}	H _{50P}	M _{50P}		
	VH _{dv}	F _{50P}	F _{50P}	VH _{50P}	H _{50P}	M _{50P}	

TABLE III: RULE SET FOR FUZZY CONTROLLER 2

		Coefficient of Friction Term Set					
		VL _f	L _f	M _f	H _f	VH _f	
% Brake Pressure Term Set	Z _{50P}	Z _{50P}	Z _{50P}	Z _{50P}	Z _{50P}	Z _{50P}	
	VL _{50P}	H _{50P}	M _{50P}		VL _{50P}	VL _{50P}	
	L _{50P}	VH _{50P}	H _{50P}	M _{50P}			
	M _{50P}	F _{50P}	VH _{50P}	H _{50P}	M _{50P}	M _{50P}	
	H _{50P}	F _{50P}	F _{50P}	VH _{50P}	H _{50P}	H _{50P}	
	VH _{50P}	F _{50P}	F _{50P}	F _{50P}	VH _{50P}	VH _{50P}	

controllers shown in Figure 1. To process each rule, we used the *minimum* operator to perform both the conjunction of the two clauses (in the rules LHS) and to fire each rule, the *maximum* operator to aggregate the outputs of the rules, and the *Center of Gravity* to summarize this aggregate and to produce a crisp output for each controller.

IV. SOLUTION ANALYSIS

After tuning the term set, the automated braking system performed very well. To validate the experiment, we used hundreds of randomly generated scenarios to test the system under different road conditions, relative velocities, and initial separation distances. Over this variety of initial conditions, the controller *consistently brought the tracking vehicle to rest within the desired safety buffer distance of 3m (±0.5m)* from the tracked vehicle. For all cases executed where preventing a collision was physically possible, the controller successfully stopped the tracking vehicle in time to prevent contact. It also stopped the vehicle in close proximity to the tracking vehicle, indicating that the brake pressure was sufficient but not excessive. For cases where the tracking vehicle started in close proximity (low separation) from the tracked vehicle the final separation distance would occasionally come in under the

three-meter “comfort zone” separation distance. This was due to the fact that the vehicle could not realistically stop much shorter. Situations like these are good examples of where an accident was probably avoided as a result of the controller.

The controller failed to stop the subject vehicle only in one case, when the two vehicles were in close proximity, the ground was slippery (low coefficient of friction), and the tracked vehicle stopped very abruptly (i.e., in situations where a collision is unavoidable due to laws of physics). This is an extremely unlikely situation, because the tracked vehicle did not operate according to the laws of physics and so it could stop very quickly regardless of the surface conditions.

The use of two controllers connected in cascade was very effective. The two controller design let us decompose the problem into two logical parts—the first controller determines the amount of brake pressure due to the tracked vehicle’s behavior, while the second controller considers the surface conditions to modify this control variable.

V. CONCLUSIONS AND POSSIBLE FUTURE WORK

Our work assumed that the subject vehicle was tracking another one on a flat, horizontal surface in a straight line. This one-dimensional analysis should be expanded to account for driving on a gradient. To simulate more realistic situations, we should also remove the assumption that the objects are moving in a straight line. A problem with this solution is that if the tracking vehicle were going around a curve, the sensors would read the velocity of the object directly in front of it, independent of the curvature. Thus, the system could be expanded to identify objects that are genuinely in the path of the subject vehicle and not incidental objects on the side(s) of the road.

In conclusion, the two-controller system trained with a genetic algorithm worked very well for the stated problem. For the cases where stopping the vehicle without a collision was possible the system consistently applied sufficient and appropriate brake pressure to stop the vehicle in time with a final separation distance of approximately 3 meters. By having a computer react immediately to a potential collision situation, accidents that could be avoided were. In situations where an accident was physically unavoidable, the controller still reacted immediately and applied a significant amount of brake pressure, minimizing the vehicle velocity at impact and thus reducing the significance of (damage due to) the collision.

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