Fuzzy Control Systems in Autonomous Vehicle Braking

Student Number 824726

***Abstract*—An exploration of the novelty and practicality surrounding autonomous braking systems as well as a case study of a fuzzy network controller for autonomous braking including an in-depth review of pertinent variables for such a system as well as a comparison of autonomous and manual braking and the differentiating factors. In addition, a guide to generating a high level prototype multi-layered fuzzy control system with an insight into rulebase weighting and evaluation of data gained including a comparison of such a system to a human driver.**

Keywords—Algorithms, Autonomous, Autonomy, Braking, Control, Fuzzy, Logic, Network, System, Vehicles,

I. Introduction

IN a world where autonomy and automation are becoming more commonplace it is only natural that autonomous automobiles are being researched by several companies. These automobiles have to be rigorously tested for safety and compatibility with human erraticness and unpredictability. In a situation such as this a clear cut solution rarely exists and we must turn to non-classical computing methodologies to solve our problems. The use of fuzzy logic has gained great acknowledgement recently as a methodology to design robust controllers of non-linear and time-variant systems *(Cabrera, Ortiz, Castillo & Simón, 2005, pp. 1).* A classical system would not be suitable for such a challenge due to the analogous, non-linear nature of the variables within such a problem.

II. Description of Problem

"MANY automobile accidents could be avoided if the correct amount of brake pressure had been applied at the proper time" *(Bonisonne & Aggour, 2001, pg. 1).* It is tricky for a machine to perform braking with the accuracy, speed and decisiveness of a human due to the number of factors (input variables) and the required accuracy of the output (braking pressure). The input variables are many and require several different pieces of equipment to measure (*Bonissone & Aggour, 2001, pp. 1,* "Performance & Validation Criteria and Scope") and measurements must be accurate to remain useful.

A system of this magnitude would have to be tested for speed by reacting faster than a human a human. A human is capable of braking at 70mph over 96 meters and 21 of those meters are thinking distance *(Driver and Vehicle Standards Agency DVSA, 2020, pp. 68).* Therefore it can be surmised that an autonomous braking system and by extension its fuzzy network controller would have to react faster than 0.671 seconds. This reaction time would include sending the signal to the brakes to begin the braking process.

It is worth noting that a fully autonomous braking system such as the one described in this paper would not have the psychological drawbacks that human braking incurs. One such example of this is an effect described by Nishant Mukund Pawar, Rashmeet Kaur Khanuja, Pushpa Choudhary and Nagendra R. Velaga although actually observed and researched by Schmidt-Daffy in 2013 (Schmidt-Daffy, 2013, pp. 14-28). Schmidt-Daffy found that "the driver's anxiety increases when the driver is unable to decide his/her preference between over-speed and safety. Further, under time pressure situations, high brake latency was observed during an animal crossing event." (Pawar, Khanuja, Choudhary & Velaga, 2020, pp. 2). Psychological phenomena such as these are inconsequential in an autonomous system as there is no human factor therefore it can be surmised that an autonomous system will be more consistent as cannot fall prey to emotion or surprise.

III. Methodology

BY using fuzzy logic, a reduced rulebase and the ideas and theories outlined in paragraph 2 of the "Solution Specification" section of Bonissone & Aggour's "Fuzzy Automated Braking System for Collision Prevention" *(Bonissone & Aggour, 2001)* I believe it is possible to create a fuzzy logic controller concise and capable enough to handle a task as complex and multifaceted as automatic braking in both a reasonable time and with the required accuracy. To speed up the system suggested in the above I will run 2 systems in parallel and use a reduced variable set.

A solution proposed in a conference paper by Piero P. Bonissone and Kareem S. Aggour relies on a "system, consisting of two fuzzy controllers connected in cascade" (*Bonissone & Aggour, 2001, pp. 1-4*). This system works thusly: the first fuzzy controller calculates the percentage of brake pressure that would be applied under "ideal conditions" based on the distance between the vehicle in front and the difference in its velocity and the velocity of the tracking vehicle. The second fuzzy controller in the cascade calculates the percentage of this pressure to apply given a set of conditions relating to road surface, brake pad material etc. The resulting percentage is taken from the brake pressure percentage determined by the first controller.

A solution to this problem must satisfy the following criteria. It must be fast, accurate and consistent. The speed of the solution obtained will be directly affected by the number of variables we have therefore a heuristic solution must be achieved, one in which only meaningful core variables are used. The accuracy of the solution will be determined by a variety of tests such as stopping at a reasonable distance in front of a stationary object, keeping a reasonable distance from a vehicle in front and reacting in an emergency stop situation. Consistency is determined by how accurate the system is over time. A system of this nature *must* always be consistently accurate as a mistake can lead to loss of life. With this being said I am not naive enough to believe a perfect system can ever be conceived therefore a fair and reasonable standard for such a system would be that the system in question is more accurate and consistent (in other words safer) than a human driver. This measurement of success will be the one that determines a usable, feasible system.

A. Network Switching

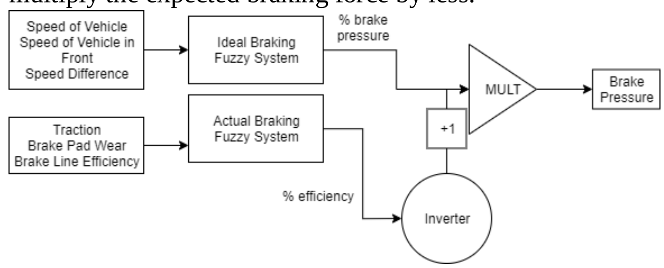
Due to the nature of some variables such as (but not limited to) brake pad material, number of pistons, caliper size and brake line diameter it would be impractical to create rulebases for every constant that may change vehicle to vehicle. Therefore I surmise that if this system were to be adopted by manufacturers a fuzzy control system would have to be created for each car model that takes into account the capabilities of that vehicle. For example, a 2005 Volkswagen Polo would have a drastically different set of constants to a 2018 Jaguar F-Pace. These constants would have to be observed and the fuzzy system controller tweaked to ensure maximum efficiency. If the Polo had the same configuration as the F-Pace then it would believe it could brake faster than it can which could lead to riskier braking and potentially an accident.

B. Input Variables

Due to the large quantity of input variables for a system of this size I have decided to reduce the number of variables I put into my system. I will also be using an adaptation of the 2 layer fuzzy network idea from the paper by Piero P. Bonissone and Kareem S. Aggour (*Bonissone & Aggour, 2001, pp. 1*).

Deciding which input variables are important and which can be removed is a tricky process and there is very little literature surrounding the importance and weighting of the various psychological, vehicular and environmental factors for braking therefore I have chosen the factors I believe to have been most commonly referenced during my investigations into this topic. I understand that this may make my data skewed therefore I would advise anyone who attempted to replicate this system to gain a deeper insight into the weighting of each factor and weight their rulebases accordingly so as to generate more meaningful data and perhaps omit superfluous variables to speed up the system.

The variables I will be using for this fuzzy control system are speed, distance to the vehicle in front, speed difference between vehicle and vehicle in front (speed difference), road wetness and/or iciness (traction), brake pad wear and brake line efficiency. These will be used to calculate the output (brake pad pressure required). A diagram showing a basic overview of the system can be seen below (fig. 1). The inverter is required due to the output "efficiency" being between 0 and 1 and, if the braking is efficient, you will multiply the expected braking force by less.



[fig. 1]

C. System Overview

A notable change of this control system compared to the one posited by Bonissone & Aggour *(Bonissone & Aggour, 2001)* is that the two fuzzy systems are working in parallel, thus allowing for a faster response time. I would also theorise that once one fuzzy system's output has been computed the processing power dedicated to running that computation could be allocated to the second fuzzy system (I am treating the MULT operation as primitive and of negligible processing power and time) thus ensuring no wasted computation power or time.

IV. Results

By starting with a weighting of 1 for each rulebase and keeping to the 6 variables described previously I am able to simulate a fuzzy control network that responds quickly (sub second response time) and, using the safe deceleration speed of 0.6409 m/s at 61-70km/h (about 38-43.5mph) as calculated by N. Omar et al. (N. Omar et al., 2018, pp. 4), calculate its performance versus the expected performance of a human driver and discuss the comparison including similarities and differences. I will also be able to tweak weightings to see how they impact the results

A. First Attempt

During the testing phase of the first fuzzy system, the system concerning brake pressure under ideal circumstances I came across a flaw with my work. Speed difference is only relevant if both vehicles are travelling at roughly the same speed (+/- 3km/h) therefore it appears to be a redundant variable however in those situations where there is a difference it becomes essential as it is the difference between a collision and a safe stop. Therefore I have decided to eliminate FrontVehicleSpeed as a variable and have a more nuanced set of membership functions for SpeedDifference. This allows me better control over IdealBrakePressure. The first iteration of my system had to be drastically reworked due to the data in fig. 2 as the figures were simply unacceptable for a safe system.

Speed (km/h)	FrontVehicleSpeed (km/h)	SpeedDifference (km/h)	IdealBrakePercent (0.x decimal)

70	68	-2	0.33
65	63	-2	0.817
69	63	-7	0.817

[fig. 2]

As shown above (fig. 2) the system treated a difference of -7 km/h as having equal severity to a difference of -2 km/h. I believe this can be fixed with rulebase weighting and the aforementioned removal of FrontVehicleSpeed.

B. Second Attempt

The second iteration of the "Ideal Conditions" fuzzy system was much more promising. The system returned expected values for each case I presented to it and the values match up well with what I would expect (fig. 3).

Speed (km/h)	SpeedDifference (km/h)	IdealBrakePercent (0.x decimal)
70	+3	0.03
70	-5	0.611
65	+5	0.363
65	0	0.03*
65	-4	0.5**
61	+3	0.03
61	-7	0.5**

[fig. 3]

* This is due to every rule having a weight of 1 and the system being told that having a SpeedDifference of "same" implies no braking is required, This can be fixed by weighting

** It is interesting to note that this system treats these 2 inputs as having the same severity. I believe that by weighting fast speeds and large negative speed differences more highly then we will see better results.

This system is still not perfect but it is a huge improvement from what we started with. It may be worth mentioning that the system as-is does not incorporate distance between the car in front and the car the system is mounted to. This factor is important however it is assumed that the driver is sensible and keeping at least the minimum requirement of 2 seconds from the driver in front.

C. Third Attempt

For this system I added the variable "SeparationDistance" and tweaked the membership function for "SpeedDifference" as well as completely rewrote the rulebase with both 0.5 and 1 weightings using 1 where "Speed" was fast or "SpeedDifference" was "Much Slower". The results of this can be found in fig. 4. It is worth noting that the recommended separation distance for a vehicle on the road is 2 seconds from the vehicle in front *(Driver and Vehicle Standards Agency DVSA, 2020, rule 126)* therefore the minimum distance you should be from the person in front can be calculated thusly:

$$\left(\frac{s}{3600} \times 1000\right) \times 2 \textit{ or more concisely } \frac{5s}{9}$$

Therefore it can be surmised that a separation distance of approximately two thirds of a vehicle's speed is "safe".

Speed (km/h)	SpeedDifference (km/h)	SeparationDistance(m)	IdealBrakePercent (0.x decimal)
70	+3	30	0.5**
70	-5	100	0.385
70	-7	30	0.847
65	+5	60	0.0413
65	0	20	0.339*
65	0	80	0.373*
65	-4	30	0.5**
61	+3	90	0.373
61	-7	20	0.847
61	-7	110	0.373

[fig. 4]

As can be seen in fig. 4 above my system is still far from perfect. Any instance where a separation distance is unsafe has been highlighted accordingly. Most notably is the case marked (*) where, despite the separation distance being significantly shorter, the system sees the larger separation distance as more severe. I believe this is due to it not knowing how to handle values nearer the centre of SeparationDistance. A more robust rulebase could definitely handle this. It is also worth noting that the system treated both lines marked ** as equally severe, something I doubt many would agree with (-4km/h difference *and* only 30m separation versus +3km/h *and* 30m separation)

D. Braking Efficiency System

Using the knowledge obtained from creating the ideal braking fuzzy system I was able to quite easily create a braking efficiency system using traction (expressed as a decimal between 0 and 1 representing the coefficient of friction between the tyre and the road surface), the brake pad wear (represented as a decimal between 0 and 1 where 0 represents a heavily damaged or non-functional brake pad whereas 1 represents a like new brake pad) and brake line efficiency (where 0 is leaking or cut and 1 is like new). The measurement of these factors is quite simple and the required technology (brake pad wear sensors, pressure valve checking and traction / friction testing) could easily be inserted into the modern vehicle.

Results for the braking efficiency system are shown below (fig. 5). As you can see the system performed moderately well with most figures looking as expected however it should be noted that there is very little variance within the system and it never leaves the boundary $0.44 < x < 0.6$ which is something that must be addressed

Traction	BrakePadWear	BrakeLineEfficiency	BrakingEfficiency
1	0.2	0.9	0.593
0.8	0.4	0.85	0.465
0.8	0.8	0.3	0.493
0.5	0.5	0.7	0.449

0.5	0.4	0.6	0.449
0.2	0.6	0.4	0.47

[fig. 5]

After changing rulebase weightings (specifically giving more weight to traction) I was able to gain some more promising results (see fig. 6)

Traction	BrakePadWear	BrakeLineEfficiency	BrakingEfficiency
1	0.2	0.9	0.624
0.8	0.4	0.85	0.5
0.8	0.8	0.3	0.49
0.5	0.5	0.7	0.461*
0.5	0.4	0.6	0.461*
0.2	0.6	0.4	0.461*

[fig. 6]

The system appears to hit a floor of around 0.46. I believe if some functions were to be applied to these results then a more meaningful value could be produced. The range of values in the second attempt is larger however which is a good sign. I believe it would be a good idea to create a function that treats the range $0.45 < x < 0.65$ as the equivalent of $0 < x < 1$

E. Case Study

The coefficient of friction of rubber on tarmac is close to 1.0 (Bird, J. O., 2017) therefore we will give it a lower bound of 0.9, for brake line efficiency and brake pad wear we can assign them both 0.9 and 0.1 respectively. If we then assume a speed of 61km/h, a separation distance of 70 meters and a speed difference of -4km/h we would expect to see a moderate to hard deceleration (expressed by the system as some percentage of brake pressure more than 0.45 but less than 0.7) If we place these values into the system we get 0.5 for the first system and 0.604 (close to our upper bound) for the second system. If we invert that we get 1 - 0.604 = 0.396. Add 1 and we get our efficiency multiplier, 1.396. Therefore our final result is 1.396 x 0.5 = 0.698 which is just within our bounds.

V. Conclusion

In conclusion, I believe that this sort of fuzzy controller will be a very powerful tool for future generations of autonomous braking, the novelty of such a system in a world where autonomous vehicles are already becoming closer and closer to a reality is staggering. While I do not believe that my system is anywhere near good enough to be used in a vehicle the work done by those referenced throughout this paper certainly prove that, with enough research and effort, humanity will be able to create the world's first truly safe autonomous vehicle using fuzzy logic, fuzzy networks and fuzzy control systems.

References

[1] Cabrera, J., A., Ortiz, A., Castillo, J., J., Simón, A., (2005). A Fuzzy Logic Control for Antilock Braking System Integrated in the IMMa Tire Test Bench., *IEEE Transactions On Vehicular Technology, Vol. 54* (pp. 1). Mechanical Engineering Department, University of Málaga, doi:10.1109/TVT.2005.853479.

[2] Bonissone, P., P., Aggour, K., S., (2001). Fuzzy Automated Braking System for Collision Prevention., *IEEE International Fuzzy Systems Conference* (pp. 1-4). Schenectady, NY 12308, USA, doi:10.1109/FUZZ.2001.1009065.

[3] Driver and Vehicle Standards Agency DVSA (2020). *Highway Code*. United Kingdom: AA Publishing.

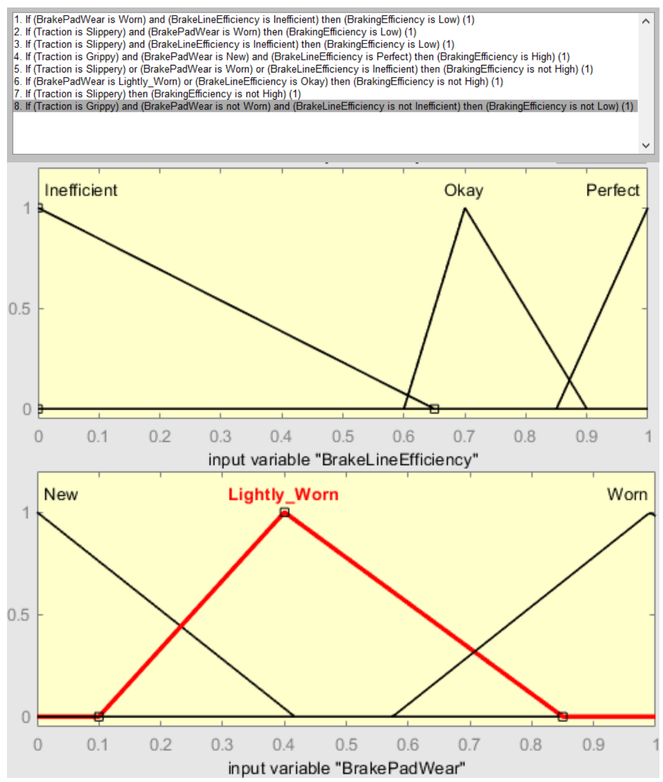
[4] Schmidt-daffy, M., (2013). Fear and anxiety while driving: differential impact of task demands, speed and motivation., *Elsevier*, Biopsychology/Neuroergonomics, Technische Universität Berlin FR 3-8, Franklinstr. 28-29, 10587 Berlin, Germany, pp. 1–28., https://doi.org/10.1016/j.trf.2012.07.002.

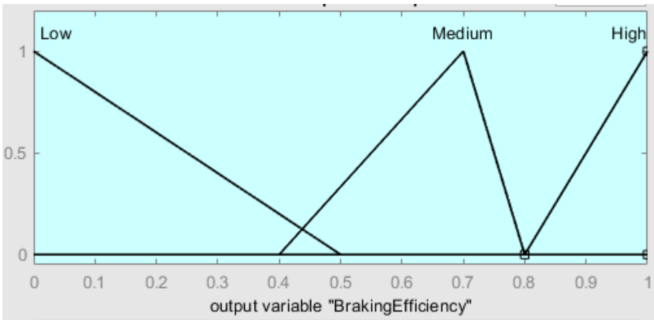
[5] Pawar, N., M., Khanuja, R., K., Choudhary, P., N., Velaga, N., R., (2020). Accident Analysis and Prevention., *Elsevier*, Transportation Systems Engineering, Department of Civil Engineering, Indian Institute of Technology (IIT) Bombay, Mumbai-400076, India, doi:10.1016/j.aap.2019.105401

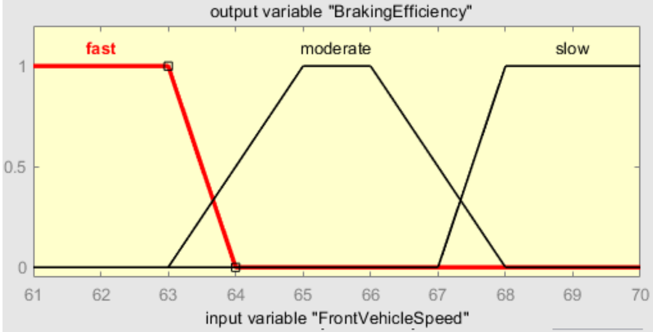
[6] Omar, N., Prasetijo, J., Daniel, B., D., Abdullah, M., A., E., Ismail, I., (2017). Study of Car Acceleration and Deceleration Characteristics at Dangerous Route FT050, *IOP Publishing*, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, doi:10.1088/1755-1315/140/1/012078

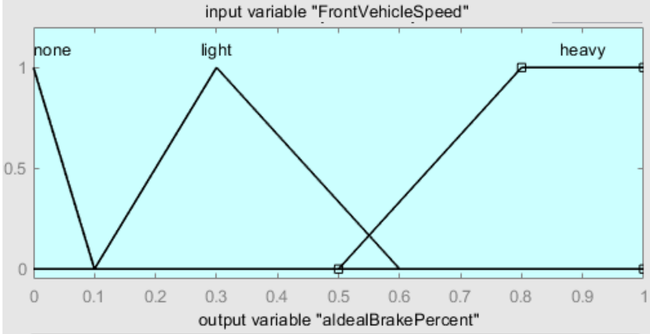
[7] Bird, J, O (2017), Coefficient of Friction, https://www.sciencedirect.com/topics/engineering/coefficient-of-friction

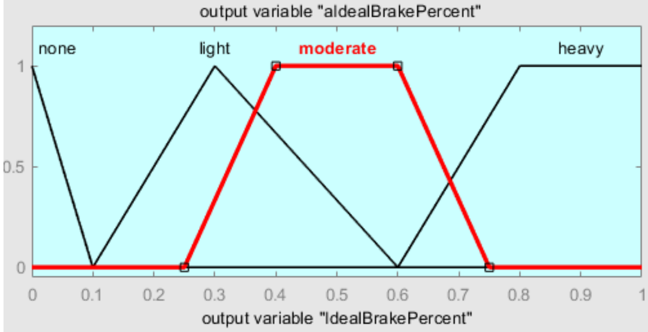
Proof of Fuzzy System Testing

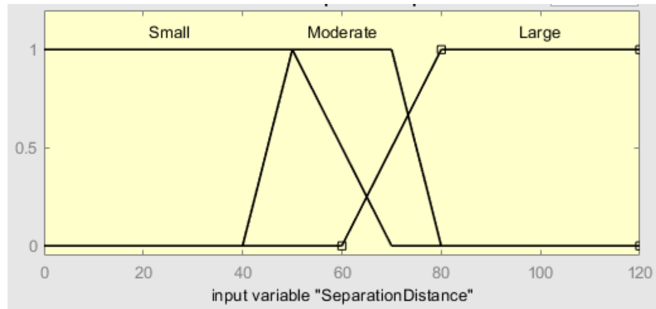


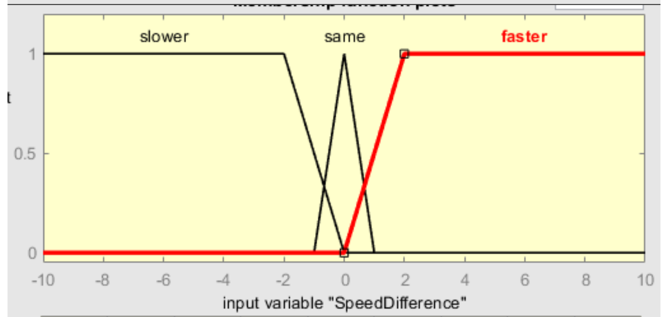


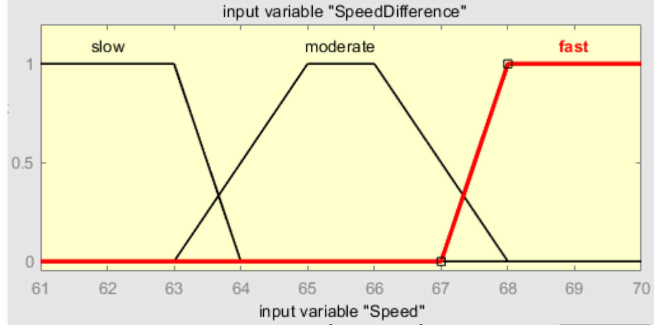


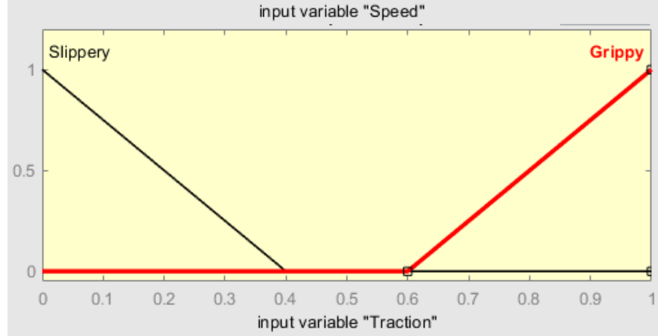












1. If (SpeedDifference is slower) then (IdealBrakePercent is none) (1)
2. If (Speed is moderate) and (FrontVehicleSpeed is moderate) and (SpeedDifference is slower) then (IdealBrakePercent is light) (1)
3. If (Speed is moderate) and (FrontVehicleSpeed is slow) then (IdealBrakePercent is heavy) (1)
4. If (Speed is moderate) and (FrontVehicleSpeed is moderate) and (SpeedDifference is faster) then (IdealBrakePercent is none) (1)
5. If (Speed is moderate) and (FrontVehicleSpeed is fast) then (IdealBrakePercent is none) (1)
6. If (Speed is fast) and (FrontVehicleSpeed is fast) and (SpeedDifference is slower) then (IdealBrakePercent is light) (1)
7. If (Speed is fast) and (FrontVehicleSpeed is fast) and (SpeedDifference is same) then (IdealBrakePercent is light) (1)
8. If (Speed is fast) and (FrontVehicleSpeed is fast) and (SpeedDifference is faster) then (IdealBrakePercent is none) (1)
9. If (Speed is fast) and (FrontVehicleSpeed is moderate) then (IdealBrakePercent is heavy) (1)
10. If (Speed is fast) and (FrontVehicleSpeed is slow) then (IdealBrakePercent is heavy) (1)
11. If (Speed is moderate) and (FrontVehicleSpeed is moderate) and (SpeedDifference is same) then (IdealBrakePercent is none) (1)

1. If (SpeedDifference is Same) then (IdealBrakePercent is none) (1)
2. If (Speed is slow) and (SpeedDifference is Slower) then (IdealBrakePercent is light) (1)
3. If (Speed is slow) and (SpeedDifference is Much_Slower) then (IdealBrakePercent is moderate) (1)
4. If (Speed is moderate) and (SpeedDifference is Slower) then (IdealBrakePercent is moderate) (1)
5. If (Speed is moderate) and (SpeedDifference is Much_Slower) then (IdealBrakePercent is heavy) (1)
6. If (Speed is fast) and (SpeedDifference is Slower) then (IdealBrakePercent is moderate) (1)
7. If (Speed is fast) and (SpeedDifference is Much_Slower) then (IdealBrakePercent is heavy) (1)
8. If (SpeedDifference is Faster) then (IdealBrakePercent is none) (1)
9. If (SpeedDifference is Much_Faster) then (IdealBrakePercent is none) (1)
10. If (SpeedDifference is Same) then (IdealBrakePercent is none) (0)