Adaptive Switching Method for Adaptive Cruise Control

Kadir HASPALAMUTGİL
AVL Research and Engineering
İstanbul, TURKEY
Email: kadir.haspalamutgil@avl.com

Erkan ADALI
AVL Research and Engineering
İstanbul, TURKEY
Email: erkan.adali@avl.com

***Abstract*—We present an Adaptive Cruise Control (ACC) architecture which is focused on solving repetitive switching issues between two modes of ACC, speed control and distance control. A cascaded controller structure has been used. First controller (upper) includes two modes: a speed controller (PI) and a distance controller (time-gap). Outputs of these controllers are acceleration reference signals. The second controller (lower) is responsible of providing the desired acceleration by controlling throttle. The switching problem occurs in most algorithms between two modes of the upper controller. In the proposed method, additional to the normal switching logic which is checking the distance with the leading vehicle, a set of logical comparisons have been used to prevent repetitive mode changing at the exact desired distance.**

***Keywords*—Adaptive Cruise Control, Time-gap control, Advanced Driver Assistance Systems, Adaptive Mode Switching, ACC Mode Switching**

I. INTRODUCTION

Adaptive Cruise Control (ACC) is a driver assist system which aims to increase efficiency, comfort and safety of the roads. Additional to the traditional Cruise Control which helps keeping a constant speed, ACC system can detect other vehicles with its sensors and maintain a distance with them. This is achieved by having at least two modes of control, Velocity control mode (Conventional Cruise Control) and Distance control mode [32, 19]. There are lots of proposed methods for distance control mode. [25] shows that even basic methods such as PI controller is enough to calculate the acceleration to keep the desired distance. [33] inspects the safety of constant space controllers and introduce string stability. [13] suggests controlling the time gap between the vehicles instead of a constant distance is safer. Gain Scheduling is also one of the common methods for distance control [23, 29]. [5] compares various methods of distance control methods including MPC. There are also some methods to optimize break throttle switching [16, 17], fuel efficiency [14], and safe switching between velocity and distance controllers. [22] offers a logical switching by comparing the desired distance with the actual distance. Some methods [6] calculate the acceleration output of the both modes and apply the minimum of the both results. However the result is jerky [18]. Other methods [2, 8, 31] includes increasing the number of modes and using distance - relative velocity graphs. While these methods are successful, in real scenarios the repetitive switching scenario occurs(figure 5).

While the vehicle approaches another vehicle under the constant speed controller, at the desired distance the system keeps switching back and forth between velocity and space controllers. In this paper, an alternative switching method is proposed which is suitable for simulations and real implementations. For the controller modes, time-gap method [15, 28] and PI controller [1] have been used and implemented on simulink. Then, the method has been tested on AVL VSM™, which is a detailed vehicle dynamics simulation software.

II. DYNAMIC MODEL

In literature, longitudinal dynamics of vehicles are well defined and these dynamics are used in many applications. According to many references, forces acting on a vehicle moving up a grade as shown in figure 1 can be expressed as follows[9, 20, 21, 24]:

$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - R_{xf} - R_{xr} - mg\ sin(\theta) \quad (1)$$

where;

F_{xf}	Longitudinal tire force at the front tires
F_{xr}	Longitudinal tire force at the rear tires
F_{aero}	Longitudinal aerodynamic drag force
R_{xf}	Rolling resistance force at the front tires
R_{xr}	Rolling resistance force at the rear tires
m	Total mass of vehicle
g	Acceleration due to gravity
θ	Angle of inclination of the road

And in small-slip region longitudinal tire forces are defined as[21, 11, 27]:

$$F_{xf} = C_{\sigma f}\sigma_{xf} \quad (2)$$

$$F_{xr} = C_{\sigma r}\sigma_{xr} \quad (3)$$

where $C_{\sigma f}$, $C_{\sigma r}$ are longitudinal tire stiffness parameters and σ_{xf}, σ_{xr} are longitudinal slip ratios. Calculation of these parameters can be found in many references[7, 30].

Aerodynamic drag force(F_{aero}) is a function of vehicle speed(V_x) and wind speed(V_{wind})[24, 3]:

$$F_{aero} = \frac{1}{2}\rho C_d A_f (V_x + V_{wind})^2 \quad (4)$$

978-1-5386-3842-2/17/$31.00 ©2017 IEEE

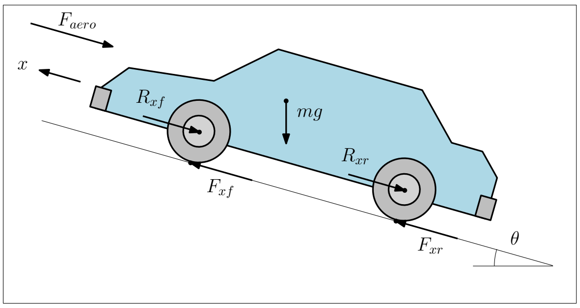

Fig. 1: Forces acting on a vehicle

where ρ is the mass density of air, C_d is the aerodynamic drag coefficient, A_f is the frontal area of the vehicle. These parameters depends on the shape of vehicle and air conditions[4, 12].

Also there is a proportional relationship(f) between rolling resistance forces(R_{xf}, R_{xr}) and tire load forces(F_{zf}, F_{zr})[21, 7]

$$R_{xf} + R_{xr} = f(F_{zf} + F_{zr}) \tag{5}$$

III. Adaptive Cruise Control

The proposed ACC method is consist of two cascaded controllers similar to [21]. The second controller(lower controller) receives the desired acceleration and outputs the actuator input (e.g. throttle angle for an engine) to provide that acceleration. The first controller has two modes: speed control mode, and distance control mode which are responsible to calculate the necessary acceleration for the vehicle to keep the desired velocity, or a safe distance with the leading vehicle, respectively. While the reference of the speed control mode is desired velocity, reference of the distance control mode is desired time-gap. The cascaded controller architecture can be seen in figure 2.

The cascaded architecture simplifies the design of the upper controllers(Figure 3). The lower controller makes sure that the actual acceleration tracks the desired acceleration. However, due to the finite bandwidth of the controller, tracking of the desired acceleration is not perfect. Hence, from the upper controllers point of view, it is assumed that there is a first order lag between the actual and the desired acceleration. As far as upper controller concerns, the system is modeled as[21]

$$\ddot{x} = \frac{1}{\tau s + 1}\ddot{x}_{des} \tag{6}$$

where τ is the lag constant.

For the constant speed mode the control law is:

$$\ddot{x}_{des} = -k_P(\dot{x} - \dot{x}_{des}) - k_I(x - x_{des}) \tag{7}$$

where $\ddot{x}_{des}$ is the desired acceleration, $\dot{x}$ is the actual velocity of the vehicle, $\dot{x}_{des}$ is the desired velocity of the vehicle, k_I and k_P are the gain values of a PI controller[1].

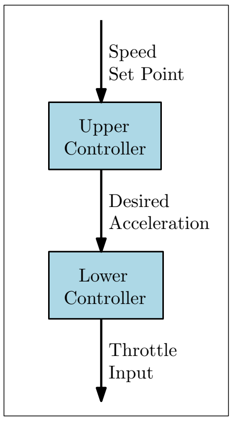

Fig. 2: Cascaded controller structure

The distance control mode uses the time-gap control developed by [13] where the desired distance is calculated as:

$$L_{des} = l + h\dot{x} \tag{8}$$

where L_{des} is the desired distance, h is the desired time-gap, $\dot{x}$ is the velocity of the following vehicle and l is the small additional constant distance for safety.
The controller is:

$$\ddot{x}_{des} = -\frac{1}{h}(l + (h\dot{x} - (x_{lead} - x))\lambda - (\dot{x}_{lead} - \dot{x})) \tag{9}$$

where $x_{lead} - x$ and $\dot{x}_{lead} - \dot{x}$ are the relative position and velocity of the leading car respectively and λ is a constant which is $\lambda > 0$ and chosen as according to low level controller performance. Also this control structure is string stable as shown as [13].

The lower controller consists of calculating necessary torque to get the desired acceleration, and calculating the necessary input (e.g. throttle angle) to provide that torque from the engine/motor. Calculating the necessary torque requires the longitudinal model of the vehicle, which also includes information about the vehicle such as mass of the vehicle, total ratio between the wheel and the engine etc. The calculation of the desired torque is:

$$(T_{req}) = \frac{J_e}{Rr_{eff}}\ddot{x}_{des} + [c_a R^3 r_{eff}^3 w_e^2 + R(r_{eff} R_x)] \tag{10}$$

where;

T_{req}	Required torque
J_e	Effective inertia reflected on the engine side
R	Gear ratio
r_{eff}	Effective tire radius
$\ddot{x}_{des}$	Desired acceleration
c_a	Aerodynamic drag coefficient
w_e	Engine angular speed
R_x	Rolling resistance force

J_e is the effective inertia reflected on the engine side which is calculated as;

$$J_e = I_e + I_t + (mr_{eff}^2 + I_w)R^2 \tag{11}$$

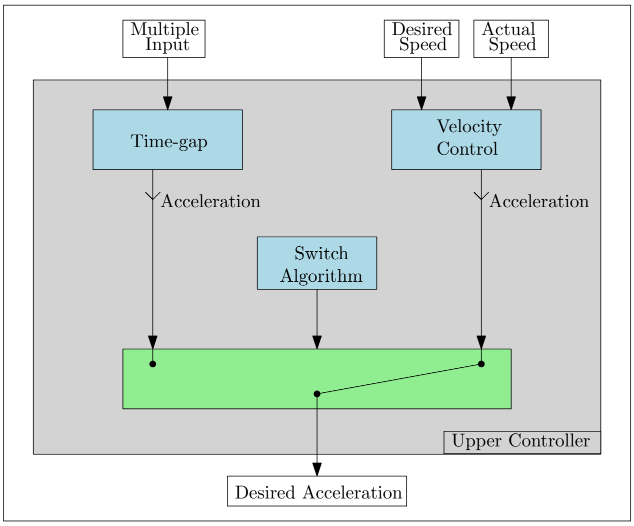

Fig. 3: Upper controller in detail

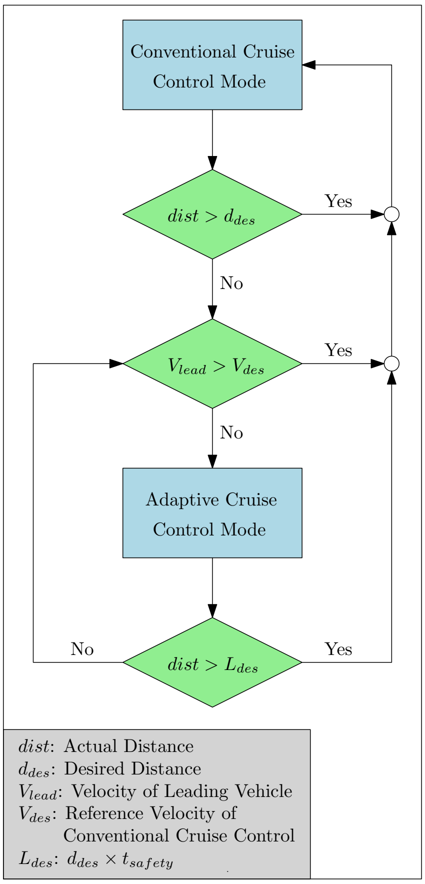

Fig. 4: Adaptive Switching Algorithm

where I_e is engine moment of inertia, I_t is transmission shaft moment of inertia, m is vehicle mass, r_{eff} is effective tire radius, I_w is wheel moment of inertia and R is gear ratio.

There are lots of different methods to control the engine to get the desired torque or acceleration such as [26, 10]. Since the lower controller is not the main purpose of this paper, a feed forward approach has been used for the AVL VSM$^{\mathrm{TM}}$simulations which is explained in section IV, and for the Simulink simulations it is assumed that a lower controller provides the desired acceleration with a phase delay, and modeled as (6).

The switching algorithm for the two modes ensures that the ACC chooses the correct mode to keep the relative distance as desired in a safe and comfortable manner. The most common method is comparing the desired distance with the actual distance and activating distance control method if the actual distance is lower than the desired one. Even though in theory it works well, when the distance controller undershoots even for a brief time, the system switches to velocity control. Under the influence of the velocity controller, the car speeds up and again switches back to distance control method. This behavior can be seen on figure 5. The proposed method solves this issue with the following algorithm. If the controller switches to distance mode, a constant(t_{safety}) close to 1 is used to increase the desired distance which results in:

$$L_{des} = (l + h\dot{x})t_{safety} \tag{12}$$

Note that this desired distance is not used in the controller. This term is used just at the proposed algorithm presented in figure 4. If the vehicle switches back to velocity control mode, then the additional distance is removed to prevent the vehicle to switch to distance control mode early. With this method, the constant back and forth switching between distance and speed controller can be solved. However, with the additional distance, the vehicle might stuck up following the lead vehicle even though it is faster than the desired velocity. To prevent this, an additional comparison is done between the leading vehicle velocity and the desired velocity. If the leading vehicle is faster than the desired velocity, then the switching algorithm switches to velocity control mode(figure 4).

IV. Simulation and Controllers

The dynamic vehicle model has been developed on Simulink to develop the algorithm. Then the implementation has been used on AVL VSM$^{\mathrm{TM}}$. AVL VSM$^{\mathrm{TM}}$is a full engine and vehicle simulation package, which is intended to simulate the longitudinal and lateral dynamics of vehicle behavior [34]. It can also be integrated with Simulink, so the actuators can be manipulated according to controller output signals. It is assumed that the relative position and velocity of the vehicle are measured by a RADAR sensor which can measure the positions and velocities of the objects with Doppler's principle and it is assumed that the measurements are perfect.

For the parameters of the following vehicle, a realistic vehicle model has been used which is provided by AVL VSM$^{\mathrm{TM}}$. For the lower controller, equation (10) has been used to calculate the necessary torque to provide the desired acceleration calculated by upper controller. Then, a throttle-engine torque map has been used to get the necessary throttle angle to control the vehicle acceleration. If the desired torque is negative, a linear map of maximum brake torque has been

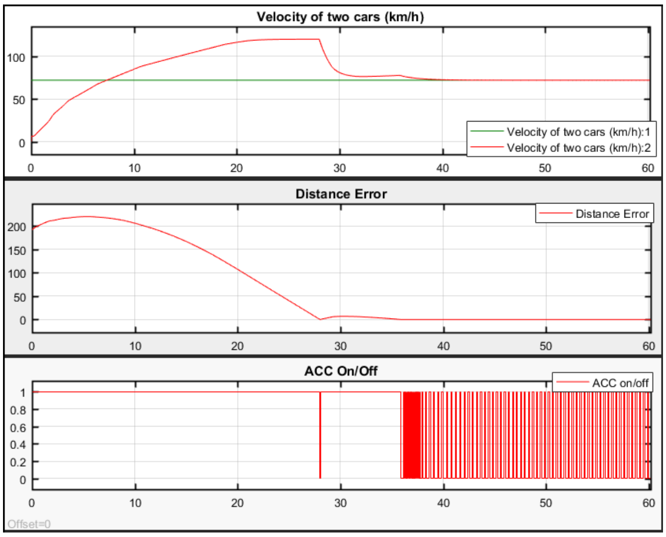

Fig. 5: Cruise control without adaptive switching

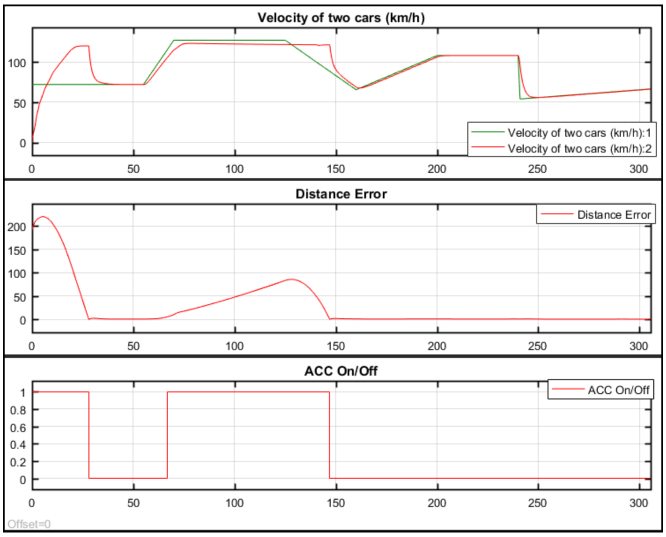

Fig. 6: Cruise control with adaptive switching

used with P gain to apply brakes instead of a throttle input. The upper controller has been designed as explained in section III. The parameters are chosen according to performance of the lower controller:

Parameter	Description	Value
l	Constant safety distance	5 m
t_{safety}	Switching safety constant	1.1
λ	Controller gain	0.4
h	Desired time-gap	1.8 s
V_{des}	Desired velocity	120 km/h

The simulation starts with a leading car which is 200 meters ahead and with an initial speed of 72 km/h. Then it increases its speed upto 127 km/h to test that if the switching algorithm switches off even if the leading car is faster than the desired velocity. The car slows down again and ramps up the speed to test the tracking performance of the distance control method. Then the vehicle makes a sudden deceleration and speeds up again very slowly.

V. Simulation Results And Discussion

Figure 6 illustrates the performance of the proposed ACC structure. The vehicle starts to speed up at the beginning until the desired distance error equates to zero. Then the vehicle switches to distance control mode, until the leading car starts to go faster than the desired velocity of the speed control mode. Although there is an additional time for the time gap controller condition, the switching algorithm compares the leading vehicle velocity with desired velocity of the speed controller and switches back to speed control mode. When the distance gets close again, it switches to time-gap control mode. We can see that the tracking performance of the vehicle is pretty good. Even though the lower controller is not perfect, the distance error is always in positive, under 1 meter, unless it is in velocity control mode. Only at one of the braking parts, the error is negative, -0.1 meters, which is way more less than our repetitive safety distance l. While following a vehicle, the controller stays in following mode even if the distance is more than the controller desires, which prevents the repetitive switching problem. You can see the result of using the same controllers without the additional logic functions to prevent constant switching problem in Figure 5. When the error is near zero, the controller switches to constant velocity mode, the distance starts to get smaller, and it switches back to distance control mode very quickly, hence the repetitive switching problem occurs. In simulation the controller can still track the desired distance with an error lower than 0.05 m. However, in a real applications repetitively braking and speeding up is not efficient, comfortable and impossible if the switching frequency is too high. With the simulations, it is shown that the vehicle moves according to what we expect from an ACC system with the proposed algorithm.

The simulations show good results however there are additional steps to be taken to implement this method on a real vehicle, which changes according to the sensors and systems on the vehicle. For example, with a vehicle with an engine control function which can provide the torque necessary for the desired acceleration, a lower controller implementation is not necessary. Similarly, if a sensor which is capable of measuring position and velocity of the objects independently such as RADAR, is mounted on the vehicle already, the implementation would be relatively easier. Implementing the controllers and switching algorithm would be relatively easy considering these functions just uses basic math and logic operations.

VI. Conclusion

This paper presented an ACC simulation model in order to control the throttle and brakes of a vehicle that does not do repetitive mode changes in the controller. A two staged cascaded controller structure has been used to deal with the non-linear dynamics of the vehicle, especially the drive train. As the upper controller two different controllers are used to control velocity and distance, depending on the desired conditions. A switching algorithm has been designed to prevent jerky or frequent switching between these modes. The lower controller calculates the necessary torque to provide the desired acceleration. Then a throttle - engine torque map is used to get the desired actuator input(throttle or brake). A realistic vehicle dynamics simulator has been used to show the performance of the proposed method. The results shown that the controller tracks the reference with a good performance.

REFERENCES

[1] Karl Johan Åström and Tore Hägglund. *Advanced PID control*. ISA-The Instrumentation, Systems and Automation Society, 2006.

[2] Z Bareket and P Fancher. Headway control systems and the heavy commercial vehicle: A case study. In *International Symposium on Heavy Vehicle Weights and Dimensions (4th: 1995: Ann Arbor, Mich.). Road transport technology–4*, 1995.

[3] William H Bettes. The aerodynamic drag of road vehicles-past, present, and future. *Engineering and Science*, 45(3):4–10, 1982.

[4] Laurence Joseph Clancy. *Aerodynamics*. Halsted Press, 1975.

[5] Daniele Corona and Bart De Schutter. Adaptive cruise control for a smart car: A comparison benchmark for mpc-pwa control methods. *IEEE Transactions on Control Systems Technology*, 16(2):365–372, 2008.

[6] S Dermann and R Isermann. Nonlinear distance and cruise control for passenger cars. In *American Control Conference, Proceedings of the 1995*, volume 5, pages 3081–3085. IEEE, 1995.

[7] Mehrdad Ehsani, Yimin Gao, and Ali Emadi. *Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design*. CRC press, 2009.

[8] P Fancher and Z Bareket. Evaluating headway control using range versus range-rate relationships. *Vehicle System Dynamics*, 23(1):575–596, 1994.

[9] Giancarlo Genta. *Motor vehicle dynamics: modeling and simulation*, volume 43. World Scientific, 1997.

[10] JK Hedrick, D McMahon, V Narendran, and D Swaroop. Longitudinal vehicle controller design for ivhs systems. In *American Control Conference, 1991*, pages 3107–3112. IEEE, 1991.

[11] Rami Y Hindiyeh. *Dynamics and control of drifting in automobiles*. PhD thesis, PhD Thesis, Stanford University, Stanford, California, USA, 2013.

[12] Sighard F Hoerner. *Fluid-dynamic drag: practical information on aerodynamic drag and hydrodynamic resistance*. Hoerner Fluid Dynamics Midland Park, NJ, 1965.

[13] Petros A Ioannou and Cheng-Chih Chien. Autonomous intelligent cruise control. *IEEE Transactions on Vehicular technology*, 42(4):657–672, 1993.

[14] Shengbo Eben Li, Huei Peng, Keqiang Li, and Jianqiang Wang. Minimum fuel control strategy in automated car-following scenarios. *IEEE Transactions on Vehicular Technology*, 61(3):998–1007, 2012.

[15] Tsang-Wei Lin, Sheue-Ling Hwang, and Paul A Green. Effects of time-gap settings of adaptive cruise control (acc) on driving performance and subjective acceptance in a bus driving simulator. *Safety science*, 47(5):620–625, 2009.

[16] Lihua Luo, Ping Li, and Hui Wang. Vehicle adaptive cruise control design with optimal switching between throttle and brake. *Journal of Control Theory and*

Applications, 10(4):426–434, 2012.

[17] Lihua Luo, Jihong Chen, and Fangwei Zhang. Integrated adaptive cruise control design considering the optimization of switching between throttle and brake. In *Intelligent Vehicles Symposium (IV), 2016 IEEE*, pages 1162–1167. IEEE, 2016.

[18] Josef Nilsson, Niklas Strand, Paolo Falcone, and Jonny Vinter. Driver performance in the presence of adaptive cruise control related failures: Implications for safety analysis and fault tolerance. In *Dependable Systems and Networks Workshop (DSN-W), 2013 43rd Annual IEEE/IFIP Conference on*, pages 1–10. IEEE, 2013.

[19] Petter Nilsson, Omar Hussien, Ayca Balkan, Yuxiao Chen, Aaron D Ames, Jessy W Grizzle, Necmiye Ozay, Huei Peng, and Paulo Tabuada. Correct-by-construction adaptive cruise control: Two approaches. *IEEE Transactions on Control Systems Technology*, 24(4):1294–1307, 2016.

[20] Hans Pacejka. *Tire and vehicle dynamics*. Elsevier, 2005.

[21] Rajesh Rajamani. *Vehicle dynamics and control*. Springer Science & Business Media, 2011.

[22] Pontus Riis. Simulation of a distributed implementation of an adaptive cruise controller, 2007.

[23] Payman Shakouri, A Ordys, Dina Shona Laila, and Mohamad Askari. Adaptive cruise control system: Comparing gain-scheduling pi and lq controllers. *IFAC Proceedings Volumes*, 44(1):12964–12969, 2011.

[24] Michael Short, Michael J Pont, and Qiang Huang. Simulation of vehicle longitudinal dynamics. *Safety and Reliability of Distributed Embedded Systems*, pages 04–01, 2004.

[25] VV Sivaji and M Sailaja. Adaptive cruise control systems for vehicle modeling using stop and go manoeuvres. *Int. J. Eng. Res. Appl*, 3:2453–2456, 2013.

[26] Jean-Jacques E Slotine, Weiping Li, et al. *Applied nonlinear control*, volume 199. prentice-Hall Englewood Cliffs, NJ, 1991.

[27] Jacob Svendenius. Tire modeling and friction estimation. *PhD Theses*, 2007.

[28] Junmin Wang and Rajesh Rajamani. Should adaptive cruise-control systems be designed to maintain a constant time gap between vehicles? *IEEE Transactions on Vehicular Technology*, 53(5):1480–1490, 2004.

[29] Glenn R Widmann, Michele K Daniels, Lisa Hamilton, Lawrence Humm, Bryan Riley, Jan K Schiffmann, David E Schnelker, and William H Wishon. Comparison of lidar-based and radar-based adaptive cruise control systems. Technical report, SAE Technical Paper, 2000.

[30] Jo Yung Wong. *Theory of ground vehicles*. John Wiley & Sons, 2008.

[31] Yao Zhai, Lingxi Li, Glenn R Widmann, and Yaobin Chen. Design of switching strategy for adaptive cruise control under string stability constraints. In *American Control Conference (ACC), 2011*, pages 3344–3349. IEEE, 2011.

[32] Gao Zhenhai, Wang Jun, Hu Hongyu, Yan Wei, Wang Dazhi, and Wang Lin. Multi-argument control mode switching strategy for adaptive cruise control system. *Procedia Engineering*, 137:581–589, 2016.

[33] Jing Zhou and Huei Peng. Range policy of adaptive cruise control vehicles for improved flow stability and string stability. *IEEE Transactions on intelligent transportation systems*, 6(2):229–237, 2005.

[34] AVL Research and Development. AVL Vehicle Dynamic Simulation. `https://www.avl.com/-/avl-vsm-4-`.