Car-following Characteristics of Adaptive Cruise Control from Empirical Data

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OBJECTIVES AND METHODS

BACKGROUND

- **Automated vehicles will affect capacity**
  - ⇒ AVs drive differently than humans, yet car-following models are based on observed human behavior.
- **Transportation agencies need car-following models of computer-controlled driving**
  - ⇒ Adaptive cruise control (ACC) systems are an early form of automation.
  - ⇒ The models used in ACC on production vehicles are industry trade secrets. Most literature estimates automated car-following models using best guesses.
  - ⇒ Car-following models should be derived from or calibrated to observed behavior of ACC systems.

OBJECTIVES

- ⇒ **Establish a car-following model that reflects the behavior of a production vehicle with adaptive cruise control**
- ⇒ **Provide guidance for modeling a vehicle with adaptive cruise control using commercial microscopic simulation software**

DATA COLLECTION

- **Vehicle**
  - ⇒ 2017 Audi Q7
  - ⇒ ACC headways of 1, 1.3, 1.8 (default tested), 2.4, and 3.6 seconds
- **Sensors**
  - ⇒ Laser scanner for measuring gap to lead vehicle, 3x/second
  - ⇒ Smartphone GPS for speed and acceleration, 1x/second
  - ⇒ Video for traffic conditions, presence of lead vehicle, ACC settings, ACC engagement, unusual traffic scenarios such as cut-ins
  - ⇒ Linear interpolation used to calculate data at 0.1 second intervals
- **Test Cases**
  - ⇒ Arterial traffic
  - ⇒ Empty road accelerations from standing

Laser scanner installed in the test vehicle.

Consolidated timestamped video of test vehicle with ACC engaged.

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MODELING

ACC CHARACTERISTICS RELEVANT TO CAR-FOLLOWING

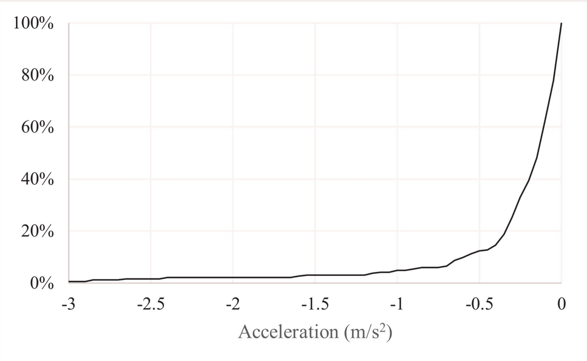
Acceleration

Vehicle Speed *(km/hr)*	0	10	20	30	40	50	60	70	**80**	90
Average Acceleration *(m/s²)*	0.36	2.02	2.10	2.66	2.36	2.01	1.75	1.53	**1.17**	0.57

Deceleration

ISO 15622 limits decelerations to –3 m/s^2.

98% of observed decelerations below **desired deceleration of –2 m/s^2** in the literature *(1,2)*



Startup Time and Distance

Measure	Average Value
Time between lead brake light off and ACC vehicle movement	2.48 s
Time between lead vehicle movement and ACC vehicle movement	1.59 s
Distance traveled by lead vehicle distance before ACC vehicle movement	1.73 m

Standstill Distance

- 8 instances between 3.35 and 4.2 meters.
- Distance of **3.5 meters** used for analysis.

INTELLIGENT DRIVER MODEL COMPARISON

IDM Formulation

$$a_{IDM} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s_0 + max\left[0, vT + \frac{v\Delta v}{2\sqrt{ab}}\right]}{s}\right)^2\right]$$

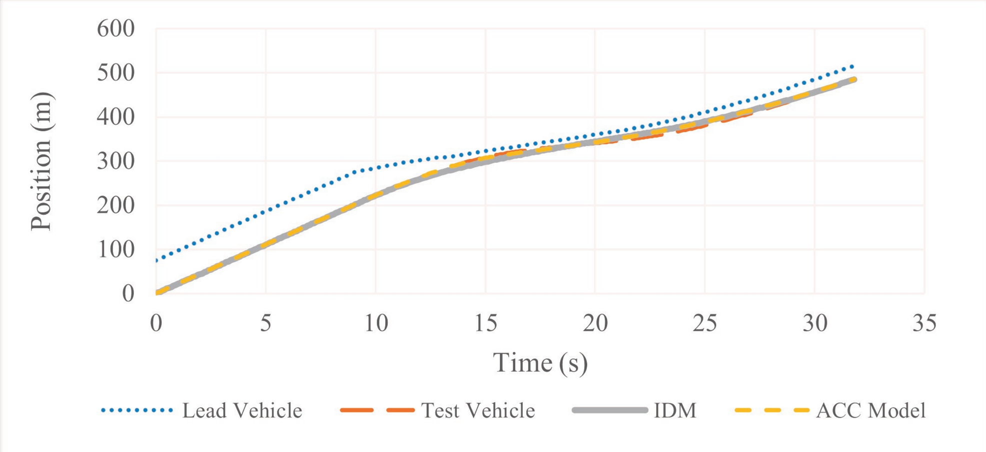
$$a_{IDM} = \begin{cases} j_{max} + a_{t-r}, & a_{IDM} - a_{t-r} < j_{max} \\ 2rb_{max} - \sum_{i=t-1}^{t+1-2r} a_i, & \frac{1}{2r}\left(a_{IDM} + \sum_{i=t-1}^{t+1-2r} a_i\right) < b_{max} \\ a_{IDM}, & \text{otherwise} \end{cases}$$

$$a_{ACC} = \begin{cases} a_{IDM}, & a_{IDM} \geq a_{CAH} \\ (1-c)a_{IDM} + c\left[a_{CAH} + b\tanh\left(\frac{a_{IDM} - a_{CAH}}{b}\right)\right], & \text{otherwise} \end{cases}$$

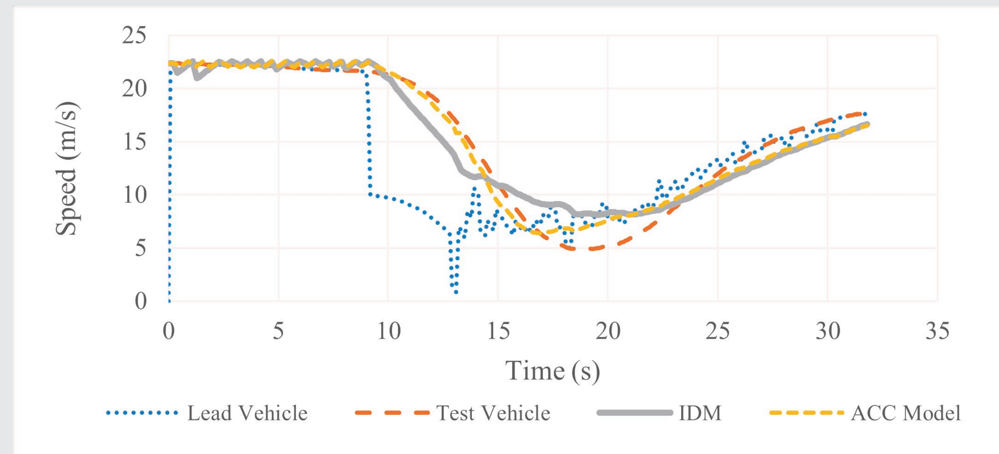
a_{IDM} = intelligent driver model acceleration, "IDM" in figures
a_{ACC} = enhanced model to reduce hard braking *(2)*, "ACC Model" in figures
a_{CAH} = constant acceleration heuristic used in calculating a_{ACC}
v = current vehicle speed
s = gap
t = current timestep
r = simulation time steps per second

Parameter	Symbol	Value	Source
Desired speed	v_0	Varies	Data
Free acceleration exponent	δ	4	*(1, 2)*
Desired time gap	T	1.8 s	*(3)*
Jam distance	s_0	3.5 m	Data
Maximum acceleration	a	2.0 m/s^2	Data, *(4)*
Desired deceleration	b	2.0 m/s^2	Data, *(1, 2)*
Coolness factor	c	0.99	*(2)*
Maximum deceleration over 2 s	b_{max}	-3.5 m/s^2	*(4)*
Maximum jerk over 1 s	j_{max}	-2.5 m/s^3	*(4)*

Field Test – Hard Braking Event



Position vs. time for vehicles and models in the test scenario.

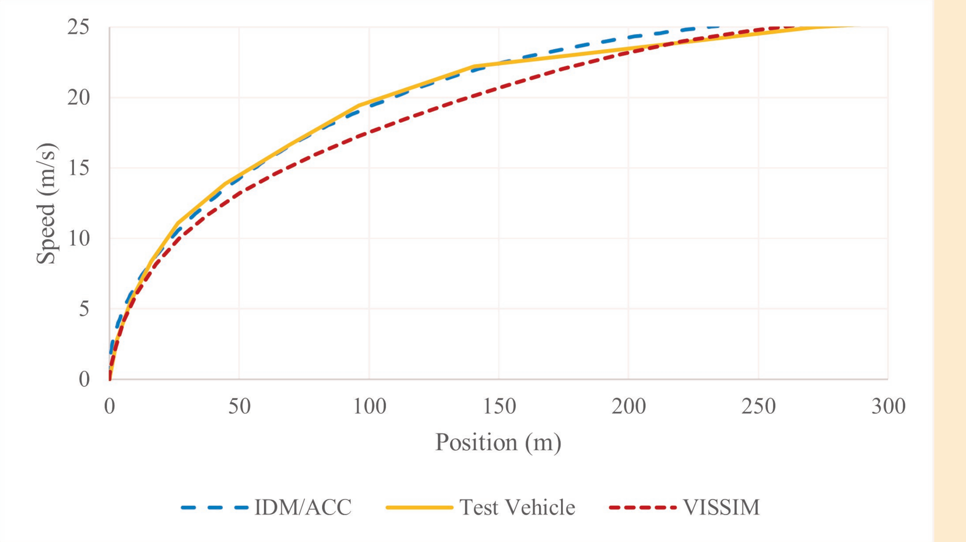


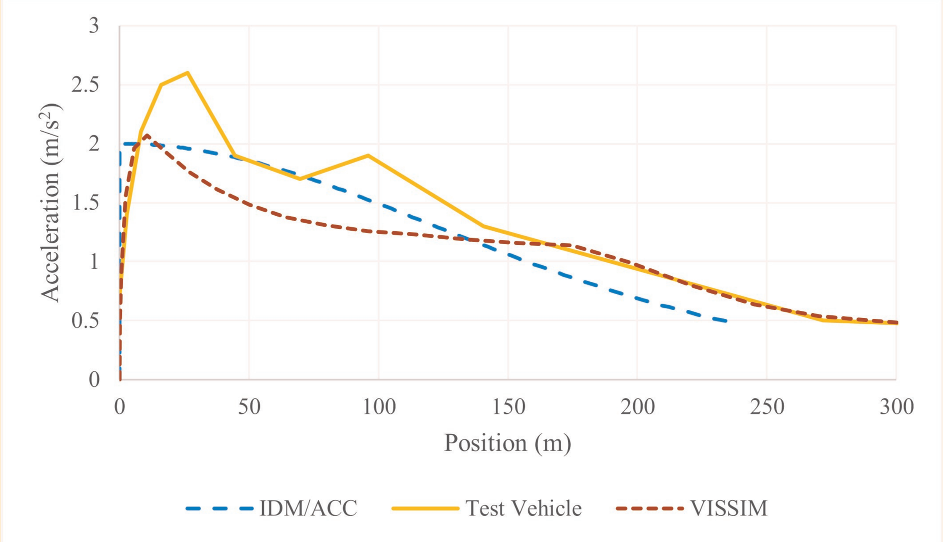
Speed vs. time for vehicles and models in the test scenario.

RECOMMENDATIONS

RECOMMENDED VISSIM SETTINGS

Wiedemann 99 Parameter	Description	Recommended Value
CC0	**Standstill distance:** The desired gap between two stationary vehicles. *Observed distance was 3.5 m.*	3.5 m
CC1	**Following distance:** The minimum desired time gap between two vehicles. *The manufacturer's default following distance was 1.8 s, although this should be altered based on known or estimated settings.*	1.8 s
CC2	**Longitudinal oscillation:** The gap distance beyond the minimum safety distance at which a vehicle will accelerate to a leading vehicle. *Test vehicle set at 1.8 s following distance would accelerate when following distance exceeded 1.9 s at speeds of 15-20 m/s, resulting in a value of 1.5 to 2.0 meters.*	2.0 m
CC3	**Perception threshold for following:** The number of seconds prior to which reaching a safety distance at which deceleration begins, expressed as a negative value. *This could not be determined from the empirical data, and so the VISSIM default was used as recommended in the literature (5, 6).*	-8.0 s
CC4	**Negative speed difference:** Threshold for negative difference in speed between leading and following vehicle for reaction during the following regime. *Values closer to zero result in more sensitive reactions to changes in lead vehicle speed. Using default value as recommended in the literature (5, 6).*	-0.35 m/s
CC5	**Positive speed difference:** Threshold for positive difference in speed between leading and following vehicle for reaction during the following regime. *Values closer to zero result in more sensitive reactions to changes in lead vehicle speed. Using default value as recommended in the literature (5, 6).*	0.35 m/s
CC6	**Influence speed on oscillation:** Measure of the impact of gap on speed oscillation, with larger values producing greater speed oscillation at longer gaps. *Using values recommended in the literature (5, 6).*	0 / (m·s)
CC7	**Oscillation during acceleration:** Limits the jerk during the first time step while a vehicle is in the free regime. *Value is taken from observations of the test vehicle's initial acceleration when starting from standstill with no leading vehicle.*	0.36 m/s^2
CC8	**Acceleration starting from standstill:** Desired acceleration when starting from standstill. *Value taken from maximum allowable acceleration in ISO 15622 (4).*	2.00 m/s^2
CC9	**Acceleration at 80 km/hr:** Desired acceleration at 80 km/hr, limited by vehicle engine. *Value taken from acceleration tests.*	1.17 m/s^2





Accelerations and speeds of unimpeded acceleration from standstill.

CONCLUSIONS

- Four attributes of production ACC measured from field data: standstill distance (3.5 m), startup time (1.59 s), accelerations (Table 2), and decelerations (effective maximum of 2.0 m/s^2).
- Sample parameters for the Wiedemann 99 car-following model were provided based on the empirical data and the literature, allowing realistic modeling of ACC and automated vehicles in the VISSIM microscopic simulation software.
- Production ACC system compared to IDM Intelligent Driver Model over a 30-second scenario exhibiting braking from 22.5 m/s to 5 m/s, the most drastic deceleration of an ACC vehicle analyzed in the car-following literature. The ACC vehicle showed less severe deceleration when encountering congestion, allowing headways of 1.3 seconds before decelerating compared to IDM's 3 second headways.

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VTRC
Virginia Transportation Research Council
VDOT
Virginia Department of Transportation