Strategies and Spacing Requirements for Lane Changing and Merging in Automated Highway Systems

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Objective

• To find the minimum safety spacing for lane changing (MSSLC) in different automated highway systems operational concept

• The minimum safety spacing is defined as one of the vehicles execute emergency brake, all the vehicles involved can stop without collision
Outline

• The longitudinal and lateral acceleration models
• Limitation of longitudinal and lateral acceleration when changing the lane
• Different automated highway systems (AHS) operational concept
  – Vehicles have different specification of sensors and communication capability
  – Trajectories of emergency braking under different AHS concepts
• Algorithm for computation of the minimum safety spacing for lane changing (MSSLC)
• Computation result of the MSSLC
System Model

Fig. 1. Vehicle about to make a lane change.
Lane changing strategies – Longitudinal Acceleration Model

Case 1: $V_d > V_0$

Case 2: $V_d \leq V_0$

Fig. 2. Longitudinal acceleration profile in the case where the vehicle speed in destination lane is higher than that in the originating one.

Fig. 3. Longitudinal acceleration profile in the case where vehicles in the destination lane move slower than in the originating one.
Lane changing strategies – Lateral Acceleration Model

\[ a_{lat} = \begin{cases} \frac{2\pi d_I}{t_{LC}^2} \sin\left(\frac{2\pi}{t_{LC}} (t - t_{lat})\right), & \text{if } t \in [t_{lat}, t_{LC} + t_{lat}] \\ 0, & \text{otherwise} \end{cases} \]  

(2.1)

• Lateral peak acceleration \( A = \frac{2\pi d_I}{t_{LC}^2} \)

• The five parameters, \( t_{long}, t_{lat}, t_{ch}, t_{LC}, a_{comf} \), completely specify a lane change strategy
Different AHS operational concepts

• Autonomous vehicles w/o visibility of leading vehicle
• Free agents – infrastructure supported/managed
• Vehicles platoons w/o coordinated braking
Autonomous vehicles (leader is visible)

Fig. 8. Autonomous vehicles: The case where the leader is “visible” by the follower.

Fig. 6. The case where the vehicle $f_1$ is “visible” by the vehicle $f_1$. 
Autonomous vehicles (leader is not visible)

Fig. 9. Autonomous vehicles: The case where the leader is not “visible” by the follower.

Fig. 7. The case where the vehicle $f_1$ is not “visible” by the vehicle $f_1$. 
Infrastructure managed free-agents

Fig. 11. Infrastructure managed free-agent vehicles.
Platoons with coordinated braking

Fig. 13. Platoons with coordinated braking and no delay.
Algorithm for the calculation of Minimum Safety Spacing during Lane Change

• Basic idea: Employ an exhaustive search technique to calculate the minimum safety spacing

• Calculate the spacing for all the possible cases, such as the time the braking is executed, which car slams on the brake

![Diagram of vehicle about to make a lane change.](image)
Result of computed minimum safety spacing

• Only the case of autonomous vehicles was considered

• Vary $t_{\text{long}}$, $t_{\text{LC}}$, $a_{\text{comf}}$, while $t_{\text{lat}}$, $t_{\text{ch}}$ fixed
  – That is, it is assumed that the spacing has already been created by some way before changing lane

• Minimum safety spacing

• Worst case braking time
  – If the emergency braking starts at this time, the required safety spacing is the maximum
Fig. 14. MSSLC for the spacing between the vehicle $L_1$ and the merging vehicle versus relative speed between lanes ($o$: $a_{corr} = 0.1$ g and $t_{L_1C} = 5$ s; $\times$: $a_{corr} = 0.3$ g and $t_{L_1C} = 5$ s; $+$: $a_{corr} = 0.1$ g and $t_{L_1C} = 10$ s).
The speed difference between the originating lane and the target lane is the main factor that affects the MSSLC. The higher the speed difference, the more the required safety spacing.
The MSSLC is sensitive with the absolute speed of the two lanes, while the worst case emergency braking time is not affected by the absolute speed.

Fig. 17. MSSLC for the spacing between the merging vehicle and the vehicle $f_{2}$ versus relative speed between lanes ($\circ: a_{\text{correl}} = 0.1 \text{ g}$ and $\tau_{L\text{C}} = 5 \text{ s}$; $\ast: a_{\text{correl}} = 0.3 \text{ g}$ and $\tau_{L\text{C}} = 5 \text{ s}$; $+: a_{\text{correl}} = 0.1 \text{ g}$ and $\tau_{L\text{C}} = 10 \text{ s}$).
Fig. 14. MSSLC for the spacing between the vehicle $f_1$ and the merging vehicle versus relative speed between lanes ($o$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_2C} = 5 \text{ s}$; $\times$: $a_{	ext{corner}} = 0.3 \text{ g}$ and $t_{L_2C} = 5 \text{ s}$; $+$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_2C} = 10 \text{ s}$).

Fig. 15. MSSLC for the spacing between the vehicle $f_2$ and the merging vehicle versus relative speed between lanes ($o$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_2C} = 5 \text{ s}$; $\times$: $a_{	ext{corner}} = 0.3 \text{ g}$ and $t_{L_2C} = 5 \text{ s}$; $+$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_2C} = 10 \text{ s}$).

Fig. 16. MSSLC for the spacing between the merging vehicle and the vehicle $f_1$ versus relative speed between lanes ($o$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_1C} = 5 \text{ s}$; $\times$: $a_{	ext{corner}} = 0.3 \text{ g}$ and $t_{L_1C} = 5 \text{ s}$; $+$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_1C} = 10 \text{ s}$).

Fig. 17. MSSLC for the spacing between the merging vehicle and the vehicle $f_2$ versus relative speed between lanes ($o$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_1C} = 5 \text{ s}$; $\times$: $a_{	ext{corner}} = 0.3 \text{ g}$ and $t_{L_1C} = 5 \text{ s}$; $+$: $a_{	ext{corner}} = 0.1 \text{ g}$ and $t_{L_1C} = 10 \text{ s}$).
Fig. 18. Worst-case emergency braking time for the spacing between the vehicle \( t_L \) and the merging vehicle versus relative speed between lanes (\( \circ \): \( a_{\text{confl}} = 0.1 \) g and \( t_{LIC} = 5 \) s; \( \ast \): \( a_{\text{confl}} = 0.3 \) g and \( t_{LIC} = 5 \) s; \( + \): \( a_{\text{confl}} = 0.1 \) g and \( t_{LIC} = 10 \) s).
Fig. 19. Worst-case emergency braking time for the spacing between the vehicle $E_2$ and the merging vehicle versus relative speed between lanes ($\circ$: $\alpha_{\text{min}} = 0.1 \text{ g and } t_{L_C} = 5 \text{ s}; \ast: \alpha_{\text{min}} = 0.3 \text{ g and } t_{L_C} = 5 \text{ s}; +: \alpha_{\text{min}} = 0.1 \text{ g and } t_{L_C} = 10 \text{ s}$).
The worst case emergency braking time also depends heavily on the speed difference.

However, the relation of speed difference with the spacing between any two vehicles differs with respect to which two vehicles are under consideration. Hence, we cannot determine when is the worst time instance for emergency braking.

Fig. 20. Worst-case emergency braking time for the spacing between the merging vehicle and the vehicle $f_\parallel$ versus relative speed between lanes ($\circ$: $a_{\text{conf}} = 0.1 \text{ g}$ and $t_{\text{LC}} = 5 \text{ s}$; $\ast$: $a_{\text{conf}} = 0.3 \text{ g}$ and $t_{\text{LC}} = 5 \text{ s}$; $+$: $a_{\text{conf}} = 0.1 \text{ g}$ and $t_{\text{LC}} = 10 \text{ s}$).
Reference