

A Density-Estimation ACC Strategy from an Empirical Traffic Flow Relation

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In traffic engineering, discussions have traditionally centered on macroscopic flow-density relations and bottleneck analysis, remaining distant from the behavior of individual vehicles. In control engineering, ACC design has focused on string stability, with few examples explicitly incorporating a "critical state" into the control law. This study observes urban expressway traffic from a vehicle-control perspective and aims to (1) identify from vehicle-perspective observation the operating point at which deceleration events concentrate, and (2) propose a deployable ACC control law that avoids this operating point.

The dataset used is ZTD from the Hanshin Expressway Wangan Route. For each clearly identified deceleration event, we measure the time difference X and position difference Y between the ego and lead vehicles at deceleration onset (downstream positive). Linear regression over many event pairs yields:

$$Y = 12X - 24$$

Eq. (1) decomposes kinematically as $Y = \bar{v} \cdot X - \bar{DHW}$, where $\bar{v}$ is the ego's mean speed during the reaction interval X and $\bar{DHW}$ is the mean headway distance (front-to-front) at deceleration onset. Thus slope 12 m/s corresponds to $\bar{v}$ and intercept -24 m to $-\bar{DHW}$. This structure matches Newell's simplified car-following model with $\tau \approx 2$ s and $d \approx 24$ m as representative time/length scales.

Stratifying observations by time headway (THW) confirms slope $\approx \bar{v}$ and $-\text{intercept} \approx \bar{DHW}$ in every bin (Table 1). Eq. (1) identifies the operating point $(\bar{v}, \bar{DHW}, \bar{THW}) = (12 \text{ m/s}, 24 \text{ m}, 2 \text{ s})$, equivalently a critical local density $\rho_c = 1/\bar{DHW} \approx 0.042 \text{ veh/m}$, at which deceleration events concentrate. Approach to this operating point is likely to initiate cascading deceleration.

The vehicle-control objective is "maintain local density below ρ_c so that the ego does not become the origin of deceleration propagation." The onboard-observable local density $\rho_{\text{local}} = 1/DHW$ is continuously monitored and time-averaged as ρ_{est} . When ρ_{est} exceeds a warning threshold ρ_{warn} , the target time gap T_h is enlarged. Embedded in IDM-based car-following with a predictive term for reaction-delay compensation, the control law is:

$$a = -k_h(T_h - T_h^*(\rho_{\text{est}})) - k_v \Delta v - k_{\text{pred}} \cdot \hat{a}_{\text{lead}}^{\text{pred}}$$

IDM-based simulation with heterogeneous drivers shows that appropriate threshold settings yield throughput improvement as ACC penetration increases (Fig. 2).

This paper derives $Y = 12X - 24$ from vehicle-perspective traffic observations, shows that it is a kinematic identity, and identifies the operating point at which deceleration events concentrate. Using this operating point as a warning line, we propose a density-estimation-type ACC that adjusts target headway based on onboard local density. The approach currently uses onboard-only sensing but naturally extends to broader V2X-based density estimation, presenting a first step toward density-estimation ACC scaling from onboard-solo implementation to connected cooperative control.

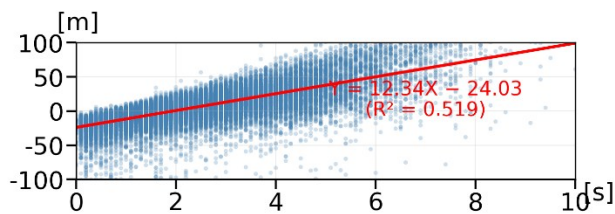


Fig. 1 Time-pos. gap to lead veh. at dec. onset

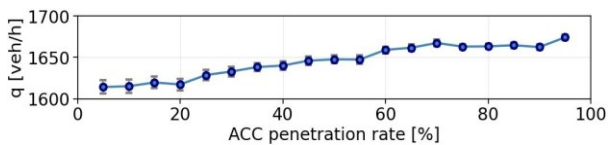


Fig. 2 Traffic-flow effect of the proposed ACC

Table 1 THW-binned regression confirming slope $\approx \bar{v}$, $-\text{intercept} \approx \bar{DHW}$

THW [s]	n	slope [m/s]	$\bar{v}$ [m/s]	$\bar{DHW}$ [m]
< 1.0	3,559	18.3	17.8	11.0
1.5 – 2.0	12,044	13.6	13.5	19.1
2.0 – 2.5	7,476	12.0	12.6	23.5
3.0 – 4.0	2,695	11.7	13.1	39.5
≥ 5.0	670	16.3	17.6	120.9
Warning pt.	-	12	12	24