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Drivers' Speeding Behavior on Expressway Curves: Exploring the Effect of Curve Radius and Desired Speed

Charitha Dias[1], Takashi Oguchi[1], and Kasun Wimalasena[2]
[1]Institute of Industrial Science, the University of Tokyo, Japan
[2]Department of Civil and Environmental Engineering, University of Ruhuna, Sri Lanka

Introduction

Speed profiles can be considered as a key input for assessing safety, comfort and efficiency of highway or expressway segments (i.e., highway design consistency evaluation in broad sense). Most previous studies have modeled the speed on highway curve sections mainly as constant or a piecewise linear profiles. Such approaches may not realistically represent the properties of speed and acceleration behavior. Further, mechanisms underlying the speeding behavior through curve sections have not been comprehensively studied.

In this study, minimum-jerk concept, which has originally been applied in neuroscience and robotics domains, is utilized to explore drivers' speeding behavior on expressway curve sections. Previous studies (e.g., Dias et al. 2017) have verified that the trajectories of turning vehicles at intersections under free-flow conditions can also be described with minimum-jerk concept. GPS-based naturalistic driving data of vehicles traveled on Tomei expressway in Japan under free-flow conditions are used to explore the applicability and validity of the proposed approach.

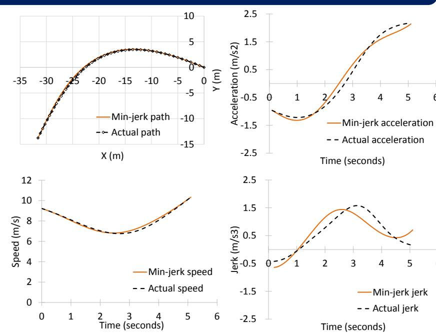


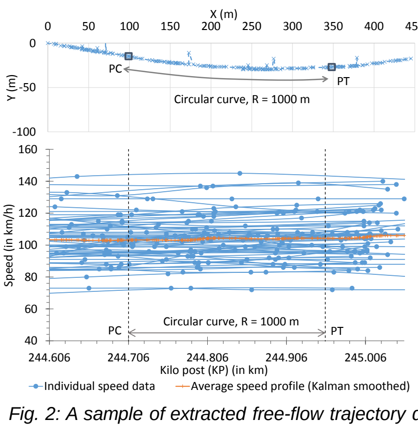
Fig. 1: Comparison of empirical and minimum-jerk trajectory of a single turning vehicle under free-flow conditions (Dias et al. 2017)
(High resolution empirical trajectories were collected through video recordings at intersections → all boundary conditions and t_f are known)

Data Sources

- ETC 2.0 data on Tomei Expressway, Japan
(GPS position, time and speed at 100 - 200 m intervals)

- Loop detector data
- Weather data
- Incident data

} *to estimate free-flow state and to extract free-flow vehicle trajectories from ETC 2.0 database*



→ Horizontal curve reconstructed from GPS data

→ An average and continuous speed profile can be obtained.
However, that does not describe the speeding and accelerating behavior

Fig. 2: A sample of extracted free-flow trajectory data

Modelling Approach

Minimum-jerk concept *by Flash and Hogan (1985):*
When moving a hand to an initial position to a final position within a given time duration t_f the cost to be minimized in order to maximize the smoothness of the trajectory is:

$$J = \frac{1}{2}\int_0^{t_f}\left(\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2\right)dt$$

Solution (*Flash and Hogan 1985*):

$$x(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5$$
$$y(t) = b_0 + b_1t + b_2t^2 + b_3t^3 + b_4t^4 + b_5t^5$$

Where; a_j and b_j (j = {0,…, 5}) are constants
(This system of equations can be solved with 12 boundary conditions and t_f)

→ Originally used to study to study optimality characteristics of skilled human arm movements, movement planning of robot limbs, motion planning and control problems in autonomous vehicles
→ Dias et al. (2017) described that turning vehicles at intersections under free-flow conditions follow minimum jerk principle

Study Site Characteristics

Study site: Tomei Expressway, Japan
The expressway linking Tokyo and Nagoya cities

» Length – 346.8 km (215.5 mi)

» Lane configuration – both 2- and 3-lane sections

» Speed limits – Mostly 100 km/h sections and few 80 km/h sections

» Horizontal curves – Ranging from 550 m to 10,000 m

» Vertical grades – Ranging from -4.9 % to +4.5 %

Fig. 3: Study area (12 horizontal curve segments on Tomei Expressway, Japan) (Source: Google maps)

Boundary Conditions to Obtain Minimum-Jerk Trajectory

Location

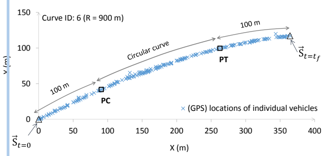


Fig. 4: Curve segment reconstructed with recorded GPS points

» Initial location: 100 m before the PC and set as (0, 0)

» Final location: 100 m after the PT and set relative to (0, 0) based on GPS data

Speed

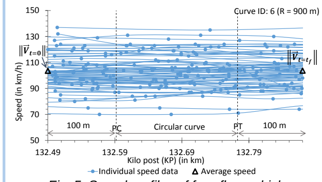


Fig. 5: Speed profiles of free-flow vehicles

» Entry and exit speeds for each trajectory was linearly interpolated from adjacent speeds and then averaged

» t_f for each trajectory was estimated from speed and location data

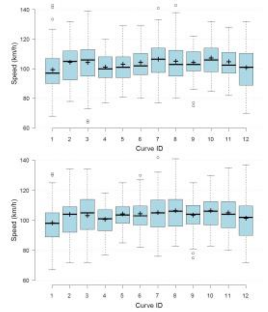


Fig. 6: Entry (up) and exit (down) speeds for different curves

Acceleration

» Assumption: individual drivers start decelerating 100 m before the PC and stop accelerating 100 m after the PT

(*Different studies reported different values for different curve radii and different speeds*

E.g., Altamira et al. (2014): 50 m – 230 m, 150 m – 170 m

Montella et al. (2015): 50 m – 200 m

*Pérez Zuriaga et al. (2013): approximately 70 m***)**

Location, speed and acceleration vectors (on X-Y plane) provide 12 boundary conditions

Results *(Estimation of speed and acceleration profiles)*

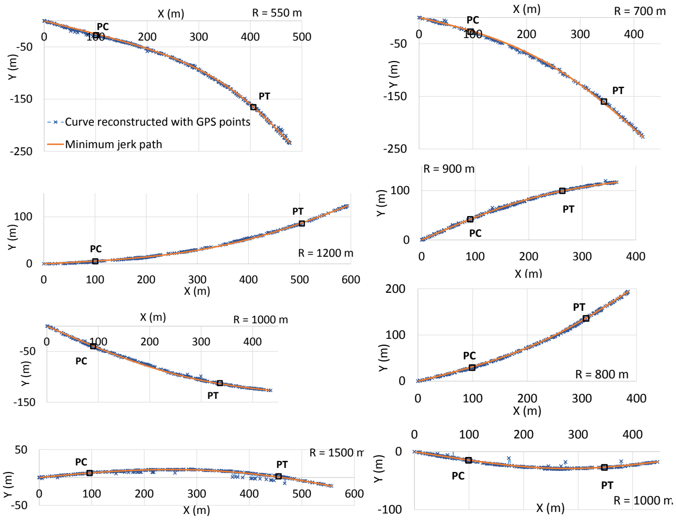


Fig. 7: Comparison of minimum-jerk and actual free-flow vehicle paths

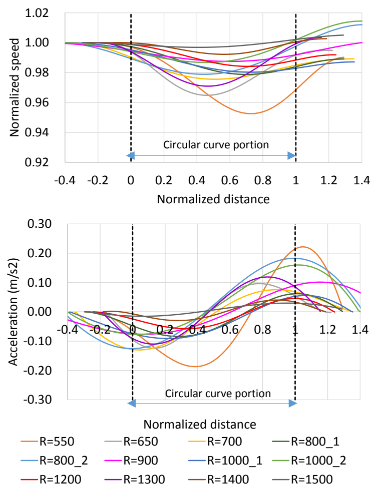


Fig. 8: Estimated normalized free-flow speed and acceleration profiles

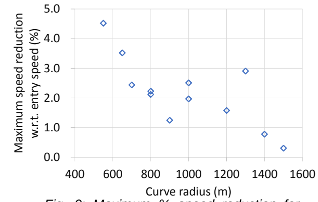


Fig. 9: Maximum % speed reduction for different curves

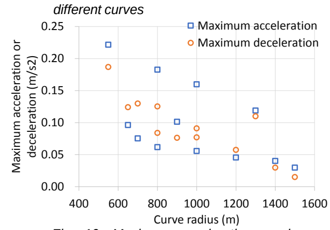


Fig. 10: Maximum accelerations and decelerations for different curves

→ Patterns are consistent with previous studies. However, validation is needed

Sensitivity *(Effect of entry speed and entry acceleration)*

Table. 1: Constants for different boundary conditions
(V: Entry/exit speed A: Entry/exit acceleration/deceleration)

	V = 100 km/h, A = 0 m/s2		*V = 123km/h, A = 0 m/s2*	
(a_0, b_0)	0.0000 ,	0.0000	0.0000 ,	0.0000
(a_1, b_1)	26.7480 ,	7.8952	32.7690 ,	9.6724
(a_2, b_2)	0.0000 ,	0.0000	0.0000 ,	0.0000
(a_3, b_3)	-0.0103 ,	0.0347	-0.0389 ,	0.0528
(a_4, b_4)	-0.0002 ,	-0.0009	0.0018 ,	-0.0009
(a_5, b_5)	2.15E-05 ,	-7.48E-06	-1.43E-05 ,	-5.15E-05

	V = 123 km/h, A = 0.1 m/s2		*V = 123km/h, A = 0.2 m/s2*	
(a_0, b_0)	0.0000 ,	0.0000	0.0000 ,	0.0000
(a_1, b_1)	32.7690 ,	9.6724	32.7690 ,	9.6724
(a_2, b_2)	-0.0480 ,	-0.0140	-0.0960 ,	-0.0280
(a_3, b_3)	-0.0247 ,	0.0585	-0.0104 ,	0.0642
(a_4, b_4)	0.0005 ,	-0.0016	-0.0009 ,	-0.0022
(a_5, b_5)	2.65E-05 ,	-3.06E-05	6.73E-05 ,	-9.78E-06

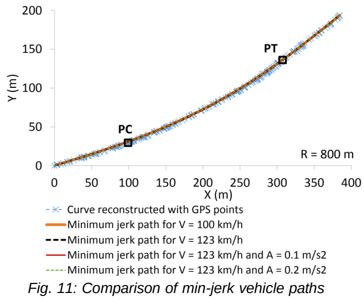


Fig. 11: Comparison of min-jerk vehicle paths for different boundary conditions

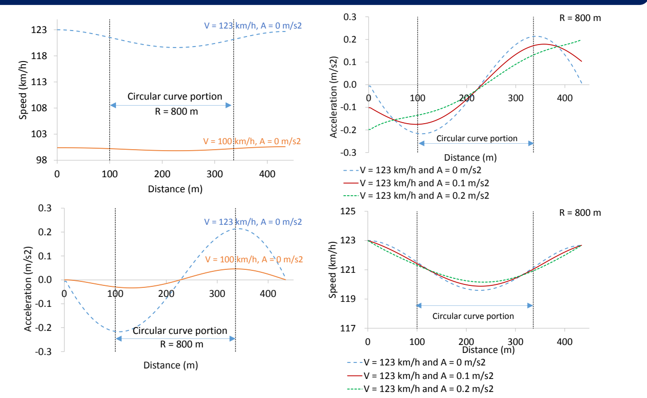


Fig. 12: Comparison of min-jerk speed and acceleration profiles for different boundary conditions

→ Different constants, but paths are overlapping

→ Speed profiles are sensitive to entry (or desired) speed

→ Speed profiles are not sensitive to entry/exit acceleration

→ Acceleration profiles are sensitive to entry/exit speed and acceleration

Summary

- Minimum-jerk concept can be applied to (indirectly) estimate speed and acceleration profiles on expressway curve segments *when entry/exit conditions and movement times are known or can be approximated*
- Effects of entry/exit accelerations and vertical grade should be further explored in future studies

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