A STUDY ON STEERING WHEEL BEHAVIOR ON CLOTHOIDAL CURVE SECTION

Yasuhiro Nonaka, Takashi Ishida, Hisao Uchiyama
Dept. of Civil Engineering, Tokyo University of Science
2641 Yamazaki, Noda-shi, Chiba #278-8510 Japan
Tel: +81-4-7124-1501(Ext.4058), Fax: +81-4-7123-9766
j7602701@ed.noda.tus.ac.jp; j7602603@ed.noda.tus.ac.jp; uchiyama@rs.noda.tus.ac.jp

Abstract

In Japan, the design methods for the plane alignment of expressway including the application of the clothoidal curve have been put into practice, but the practical adequacy has not been verified yet. This study aims to obtain the actual steering wheel behavior data on the clothoidal curve sections and to compare actually observed trajectory with that of theoretically designed. In order to establish it, the study develops the data obtaining system on the basis of a floating survey, and the number of clothoidal sections on which the valid data are obtained is 280 on the several sections of the Metropolitan Expressway.

The study results in the demonstration that the developed system here works well to collect the behavioral data on the clothoidal section. It shows that the discrepancy between theory and practice appears in some sections. For the discrepancy, the study proposes the other transitional curve that the trajectory is designed by revolving a steering wheel in the uniform angular acceleration. In this context, it also suggests as a conclusion that the different curve is worthwhile to be examined and created on such transitional sections where the relatively deep gap from the clothoidal curve is observed.

Keywords: Road alignment planning; Clothoidal curve and steering wheel behavior
Topic Area: A1 Road and Railway Technology Development

1. Introduction

The clothoidal curve is well known as the vehicle running trajectory when a driver revolves the steering wheel with constant angular speed under uniform driving velocity. Therefore the application of the clothoidal curve to a transitional curve on the expressway is considered to be reasonable for the smooth operation of the steering wheel.

In Japan, the design methods for the plane alignment including the application of the clothoidal curve, which were introduced by German engineers after the World War II, have been put into practice. In addition to the role on this transitional section, the clothoidal curve has been regarded as playing more important role on an element of expressway alignments. In fact, around 50% of the total length of 7,197kms interurban expressways in Japan is composed of the clothoidal curve at this moment. No issue, however, has reported the observation of the actual operation of the steering wheel, which means that the practical adequacy has not been verified yet.

The study aims (1) to obtain the actual steering wheel behavior data of vehicles running on the clothoidal curve sections, (2) to compare actually observed trajectory with that of theoretically designed, (3) to discuss the discrepancy from the theoretically designed trajectory and (4) to suggest the application of an effect of new transitional curve.

2. Actual steering wheel behavior

2.1 Data collection

The data obtaining system, which is developed here, is composed of a couple of subsystems, obtaining a steering wheel behavior and obtaining a vehicle running behavior respectively as illustrated in Fig.1.

On the basis of a floating survey, the time serial data for momentary velocity and accumulative running distance of the vehicle are automatically recorded to a notebook computer using the pulse signal, while the change of the angle in the steering wheel is observed time-to-time by the digital video image installed in the vehicle.

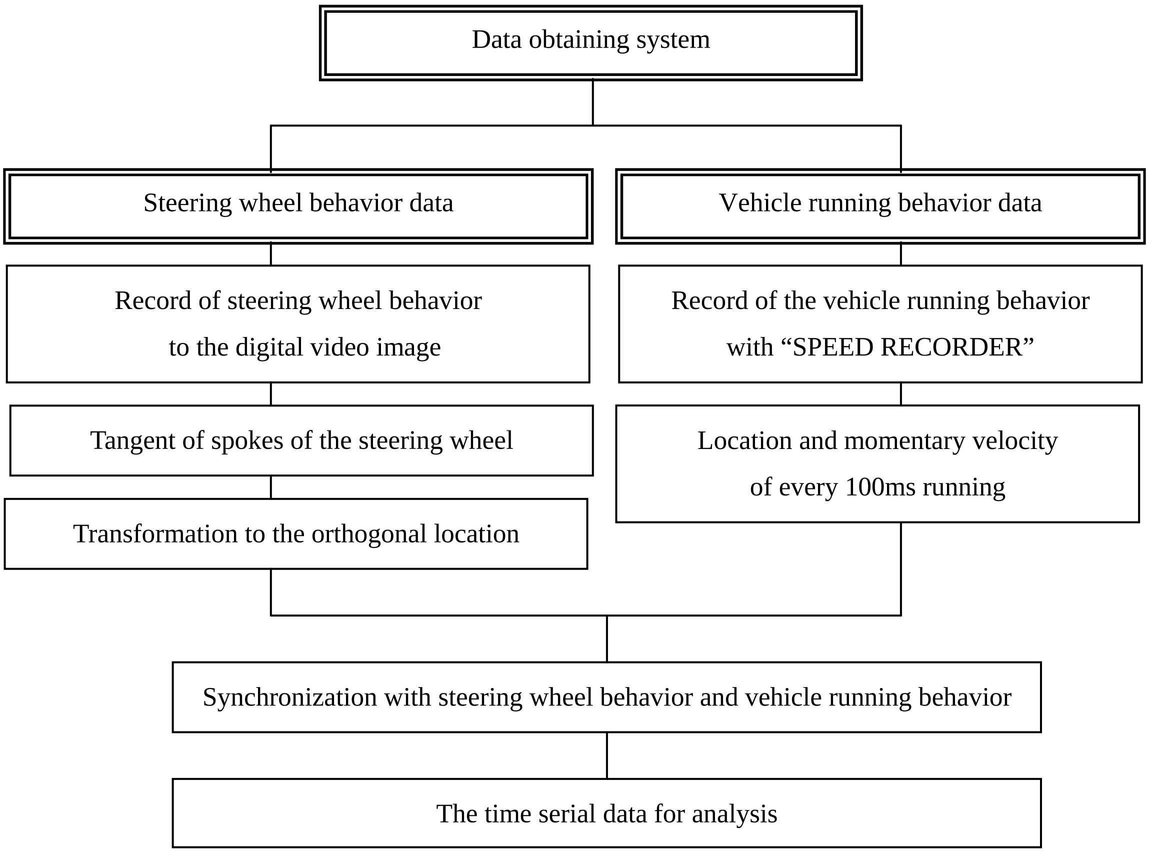

Fig.1 Date obtaining system

2.2 Steering wheel behavior

A white colored rectangular marker is pasted on the center of the steering wheel and several markers are also pasted on the grip peripherally in advance as shown in Fig.2.

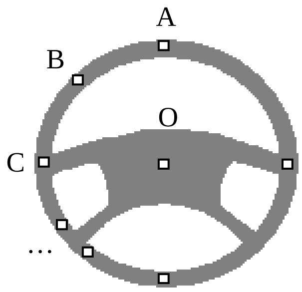

Fig.2 White colored rectangular marker

The steering wheel behavior is taken and recorded as continuous images that are converted to the bmp file in 1/10-second frame unit. As displayed in Fig.3, after conversion of the image to the binary form of black and white, the white colored markers are so conspicuous that those locations are clearly reflected on the binary image.

The center of gravity of each marker is calculated and assigned as the point of pixel coordinate (x, y) of the binary image. White reference to the tangent of the spokes, OA, OB, … , the movement of the angle of the steering wheel is derived from both of adjacent successive image. Those obtained angles are transformed to the orthogonal location.

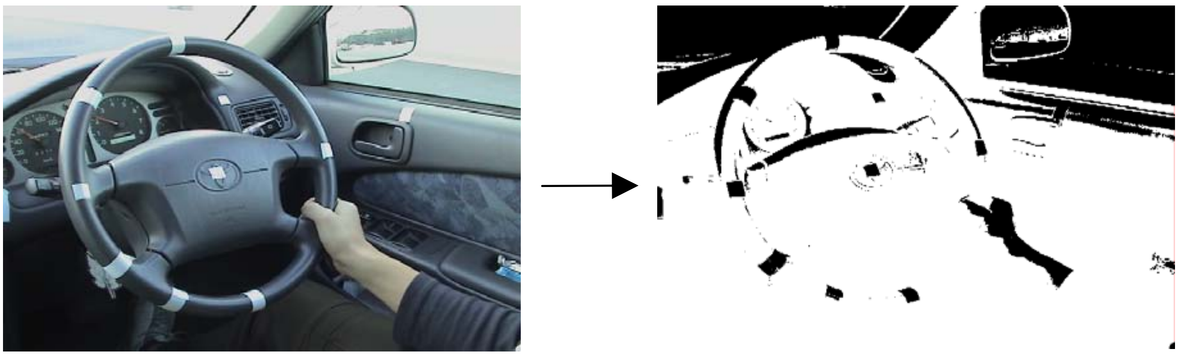

Fig.3 Original and binary form of video image

2.3 Vehicle running behavior

The vehicle running behavior is monitored by the “SPEED RECORDER” installed in the vehicle, which records the vehicle running data (momentary driving velocity and accumulative distance from the start of the vehicle) to the notebook personal computer automatically. The recorder was developed by “HIGHWAY PLANNING Inc.”.

An operator in the vehicle pushes a trigger of the recorder watching the kilo-post standing on the roadside by 100ms running, then such data as the velocity and the distance are obtained by every 100ms. The voice informing the location in connection to pushing the trigger is simultaneously sent to the digital video recorder for the movement of the steering wheel.

Thus, the movement of the vehicle and the movement of the steering wheel are synchronized with each other.

3. Initial findings from floating survey

3.1 Floating survey

The floating survey is conducted on the several sections of the Metropolitan Expressway. Three different testes drive a floating vehicle sometime on the same sections and the other time on the different sections. The number of clothoidal curve sections on which the valid data are obtained is 280. The floating vehicle maintains uniform running speed of 60km/h, since the survey is carried out in the time zone when the smooth traffic flow appears.

3.2 Trajectories of steering wheel behavior

Fig.4 shows some typical trajectories of the angular behavior of the steering wheel, where a light line corresponds to the observed trajectory of the behavior while a dark line to that of the theoretical (straight, clothoidal and circle) movement.

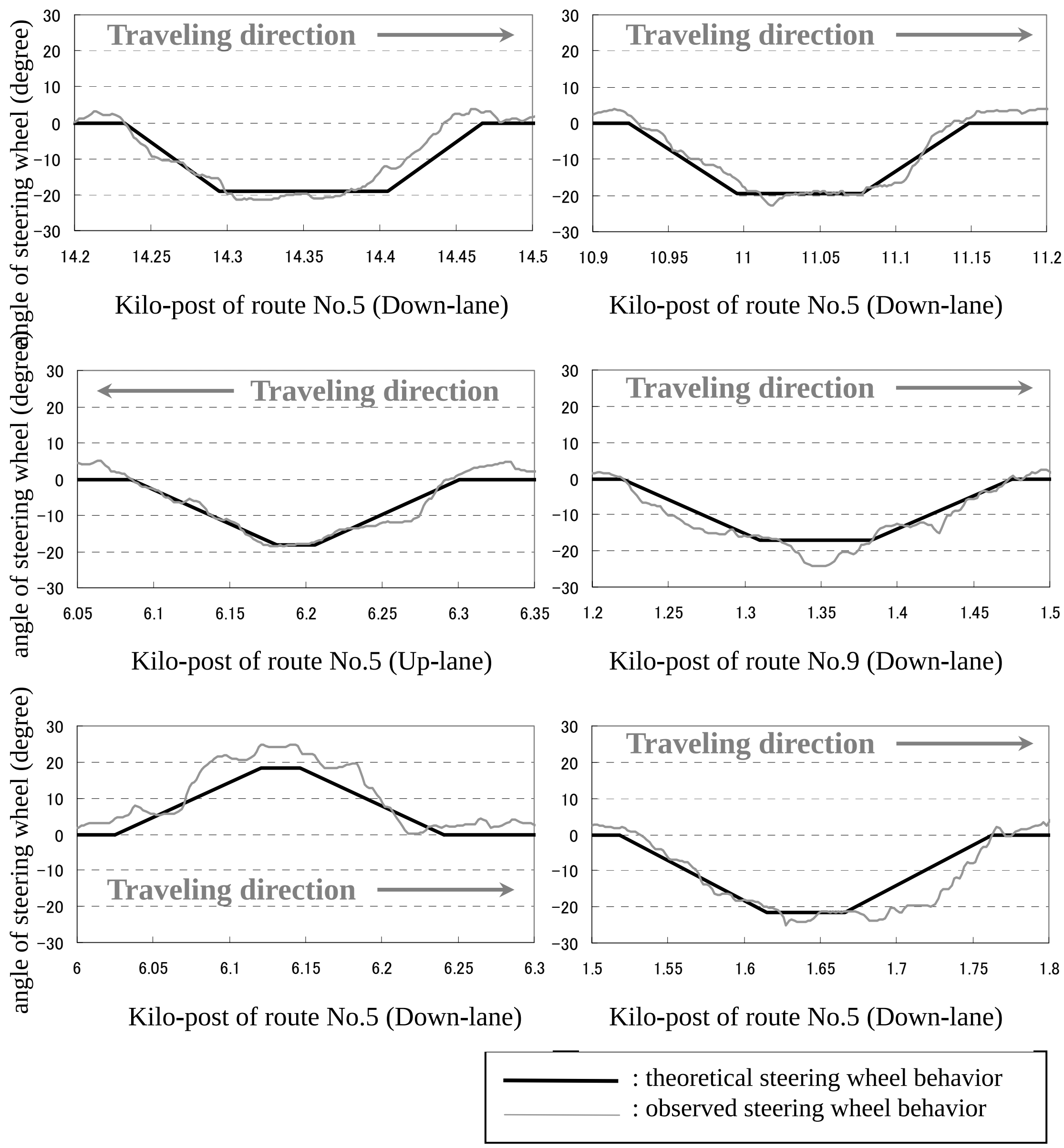

Fig.4 Change in the angle of the steering wheel

It is illustrated that the actual behavior of the steering wheel as a whole traces the theoretical line with some swinging from side to side. Focusing on the clothoidal curve section in particular as shown in Fig.5, the gap between theory and practice has a tendency to be larger rather than on the often section.

Fig.6 shows the change in the angular speed of the steering wheel on the same section of Fig.5, which confirms that a driver does not resolve it with the constant angular speed under the uniform driving velocity. From the shape with arrow marks in Fig.6, the constant angular acceleration may be analogized.

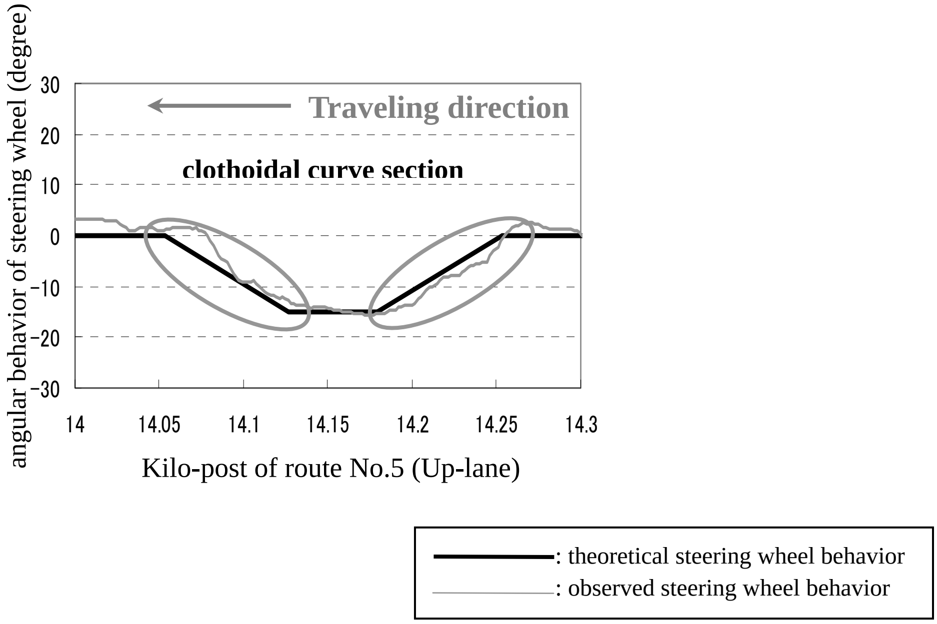

Fig.5 Angular behavior of steering wheel at clothoidal curve section

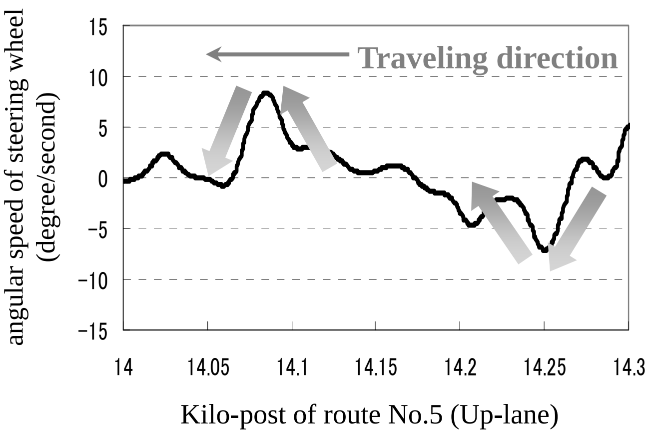

Fig.6 Change in angular speed of steering wheel at clothoidal curve section

4. An approach to acceloidal curve

4.1 What is acceloidal curve?

The study is to try to fit the curve to a different spiral curve whose trajectory is designed of revolving a steering wheel with the uniform angular acceleration, which is called as "acceloidal curve" hereinafter.

The acceloidal curve of which concept was already introduced by Dr. Hans Lorenz[6)] is defined as follows;

$$R(t) \times L^2(t) = A^3 \quad \text{(Eq.1)}$$

where

$R(t)$	;	Curvature radius of the alignment at time t (m)
$L(t)$	;	Accumulative distance at time t from time 0 (m)
A	;	Acceloidal parameter (m)

The relation of $R(t)$ and $L(t)$ is illustrated for reference in Fig.7, in which time 0 means the standing point of the curvature alignment where $R(0)$ indicates infinity and $L(0)$ is equal to 0.

In general, the spiral curve is described as Eq.2. A clothoidal curve is obtained when n is equal to 1, while an acceloidal curve when n is equal to 2 as shown in Fig.8.

$$RL^n = A^{n+1} \quad \text{(Eq.2)}$$

Fig.9 displays the difference in the angular behavior of the steering wheel between the clothoidal and the acceloidal curve.

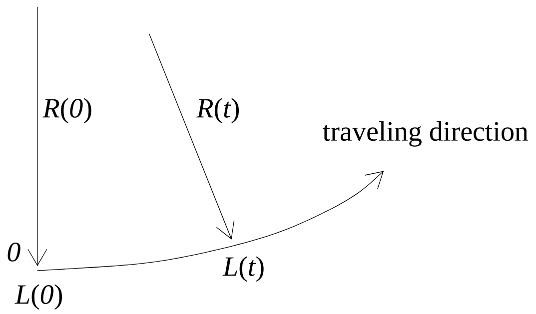

Fig.7 $R(t)$ and $L(t)$ on transition curve

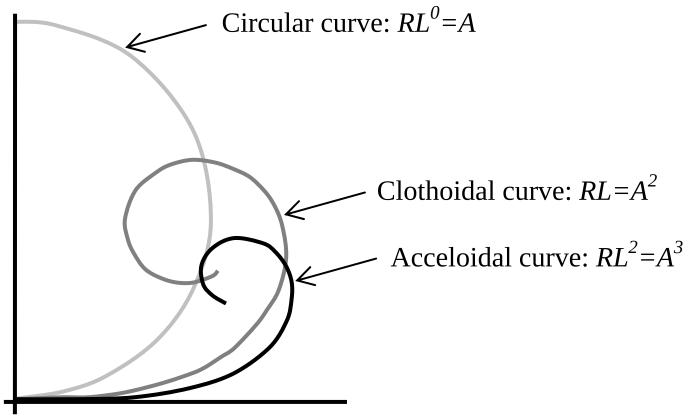

Fig.8 Pattern diagrams of structural formula

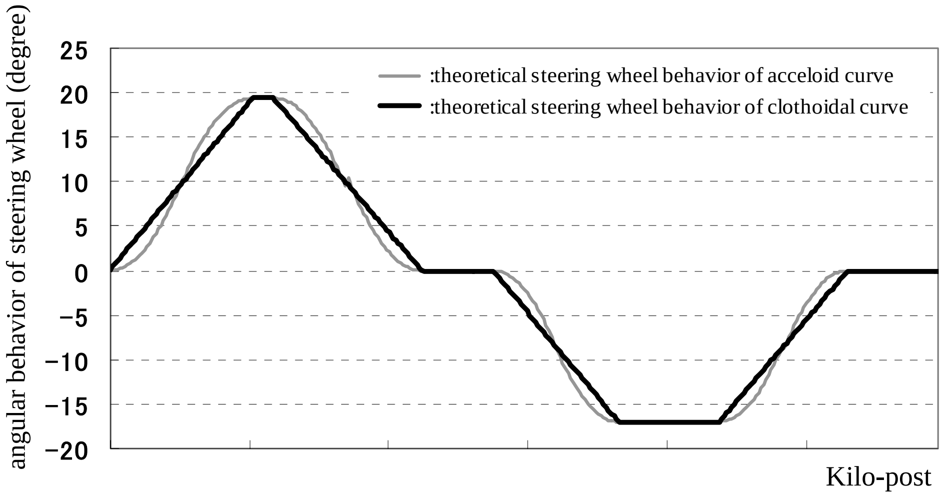

Fig.9 Comparing between the theoretical steering wheel behavior of acceloidal curve and that of clothoidal curve

4.2 Simple comparison of fitness between clothoidal and acceloidal curve

The discrepancy between the observed and the theoretical trajectory of the steering wheel is derived here. Then using the root mean square, which of the clothoidal or the acceloidal curve is much closer to the observed is simply compared.

Tab.1 summarizes the result of such comparison of all 280 sections, where 157 sections (56%) approximate to the clothoidal curve while 120 (43%) to the acceloidal curve. This may suggest that the case exists where an acceloidal curve works much more effectively than a clothoidal curve.

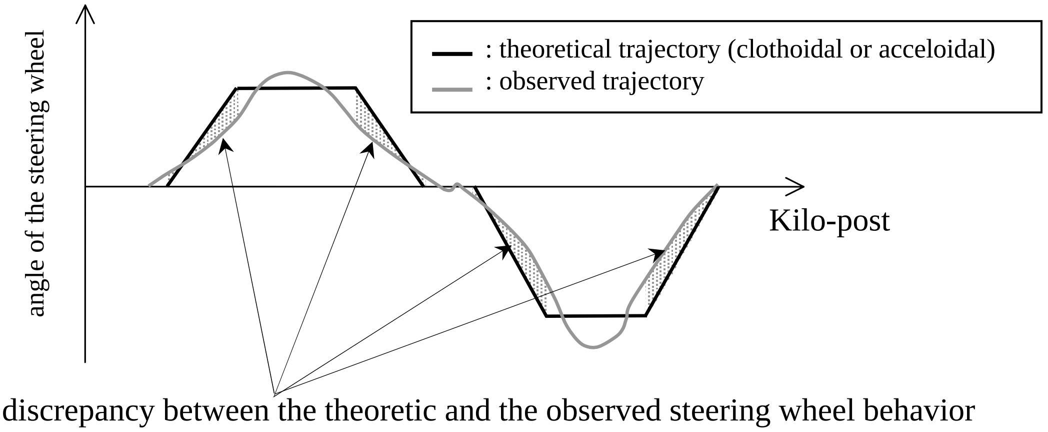

Fig.10 Discrepancy

Tab.1 Which is much closer to the observed curve?

	Approximating to clothoidal curve	Approximating to acceloidal curve	Neither of both curves	Total
The number of sections (rate)	157 (56%)	120 (43%)	3 (1%)	280 (100%)
Average (deg.)	1.62	1.72	2.24	-

5. Further findings from statistical analysis

A statistical approach is attempted to examine what elements of the alignment cause such gaps from the spiral curve. A quantification theory No.1 is applied here using following an external criterion and explanatory variables;

[External criterion] Obtained root mean square in previously chapter (*deg.*)

[Explanatory variable] Clothoidal parameter *A* (*m*)

Adjacent curvature radius to the successive alignment *R* (*m*)

Adjacent curvature length to the successive alignment *D* (*m*)

Direction of the curve to the right or left

Entrance and exit alignment of the curve

A couple of models are calibrated and the category scores are estimated as listed in Tab.2 and Tab.3 respectively. The former corresponds to a group of the sections approximating to a clothoidal curve where the discrepancy is measured from the clothoidal curve, and the latter does to a group of those of an acceloidal curve where the discrepancy is from the acceloidal curve.

The adjacent curvature radius to the successive alignment and the clothoidal parameter show rather large range of almost 1 degree in comparison with the average root mean square of 1.62 degree in the acceloidal and 1.72 in the clothoidal curve. It is understood intuitively that larger and larger the adjacent curvature radius to the successive alignment becomes, smoother and smoother the steering wheel behavior is stabilized on the both spiral curve.

It should be emphasized that the clothoidal parameter has a tendency to strongly affect smooth driving along the alignment. It is pointed out that the clothoidal curve is much suitable in case that the parameter is large as well as the acceloidal curve is accommodated to an area of the small parameter. It is also observed that the acceloidal curve well functions under A<100m, while the clothoidal curve effectively works in the area of A>100m.

Tab.2 Estimated statistics for clothoidal curve

Explanatory variable	Category	Category score (deg.)	Range (deg.)	Partial coefficient of correlation
Clothoidal Parameter $A(m)$	50-100	0.532	0.898	0.410
	100-150	-0.218		
	150-200	-0.283		
	200-250	-0.366		
Adjacent curvature radius to the successive alignment $R(m)$	-150	0.324	0.850	0.439
	150-200	0.317		
	200-250	-0.261		
	250-300	-0.371		
	300-350	-0.453		
	350-	-0.526		
Adjacent curvature length to the successive alignment $D(m)$	0-30	0.228	0.418	0.217
	30-60	-0.059		
	60-90	-0.190		
	90-	-0.105		
Direction of the curve to the right or left	Right	-0.002	0.004	0.003
	Left	0.002		
Entrance and exit alignment of the curve	From straight to circle	0.066	0.163	0.133
	From circle to straight	-0.097		

Multiple correlation coefficient: 0.733
Coefficient of determination: 0.538

Tab.3 Estimated statistics for acceloidal curve

Explanatory variable	Category	Category score (deg.)	Range (deg.)	Partial coefficient of correlation
Clothoidal Parameter $A(m)$	50-100	-0.665	1.011	0.419
	100-150	-0.083		
	150-200	0.346		
	200-250	0.267		
Adjacent curvature radius to the successive alignment $R(m)$	-150	0.876	1.461	0.660
	150-200	-0.163		
	200-250	-0.109		
	250-300	-0.120		
	300-350	-0.467		
	350-	-0.585		
Adjacent curvature length to the successive alignment $D(m)$	0-30	-0.153	0.336	0.231
	30-60	0.097		
	60-90	-0.025		
	90-	0.183		
Direction of the curve to the right or left	Right	0.027	0.056	0.059
	Left	-0.029		
Entrance and exit alignment of the curve	From straight to circle	-0.205	0.325	0.334
	From circle to straight	0.120		

Multiple correlation coefficient: 0.743
Coefficient of determination: 0.552

6. Conclusion

The study demonstrates that the developed data collecting system here well traces the trajectory of not only the vehicle movement but also the steering wheel behavior. It reveals that the discrepancy between theory and practice of the trajectory appears in most clothoidal curve sections. With regard to the discrepancy, it takes into account of a different transitional curve named an acceloidal curve of which trajectory is designed of revolving a steering wheel with the uniform angular acceleration.

The study concludes that the acceloidal curve is worthwhile to be introduced and examined on such transitional sections as the relatively deep gap from the clothoidal curve is observed. In this context, it may suggest high applicability of the new curve to the interchange sections where quite small clothoidal parameters and curvature radiuses are obliged to be adopted because of the constraint to the land acquisition in Japan. In order to verify these conclusion and suggestion derived here much precisely, however, it necessitates collecting more and more behavioral data.

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