A DISTANCE-BASE MATCHING MODEL FOR CLASSIFYING TIRE-MARKS AT ACCIDENT SCENE

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Abstract： This study proposes a distance-base matching method to classify tire-marks belonging to which car's tires at accident scene. The method employs geometric-mapping relationships from tires' treads to their tire-marks formed by car braking. The relationships ensure the actual widths of grooves and tread-elements on the lateral section of tire-tread being almost equal to the corresponding widths of the heavy and light streaks (striations) on the lateral section of tire-marks. Because the formation of tire-mark is influenced by factors such as pavement condition, types of tire-tread and material, tire's load and inflation pressure, etc., the magnitude of changes among the widths of light and heavy streaks on tire-mark are correlated. The generalized distance is used to measure the similarity for pairs of these items on tire-tread and their corresponding tire-mark. This method is validated and tested by empirical data. The results show that the tire-marks can be effectively identified and can be applied and referred by policemen/investigators in tire-marks investigation and identification.

Key Words：Accident Scene, Matching Model, Tire-marks, Tire-tread, Similarity

1. INTRODUCTION

The data of tire-marks is important evidence in accident investigation. It can be used to presume the impact locations and driver's behaviors as well as vehicles' heading, minimum speeds before the collision, and post collision trajectories, etc., in accident reconstruction. Especially, it can be used to auxiliarily identify the possible tire involved and reduce the scope of vehicles' investigation in the case of hit and run accidents. In practice, tire-marks can be recognized by investigators/policemen using a simple skill such as the vehicle heading from the drivers' description, the relative distance and orientation between the stopped vehicles and the tire-marks etc. The judgment based on drivers' descriptions and investigators' experience and knowledge frequently resulted in argumentation when drivers had inconsistent statements or investigator faced with a high complexity of accident scene such as multi-cars accident with new and old tire-marks irregularly distributed on the roadway. In addition, investigators seldom employ the texture properties of tire-marks to undertake the classification due to difficulties on its measurements judged by human eyes. Therefore, it is an important issue to develop an identification approach to classify the tire-marks in accident investigation.

Tire-marks can be divided into two classes (Baker and Fricke, 1986). One is imprint that is a mark on a roadway surface made without sliding by a rolling tire. It usually has complete geometric texture as the pattern of tire-tread. The other is tire friction mark that is a mark on a roadway surface made by a slipping or sliding tire rubbed on the road (Reveley, Brown and Guenther, 1989). The later one has two primary types, namely, skid-mark and scuffmark. A skid-mark is made by a tire sliding without rotation on a road due to braking, collision damage, etc. A scuffmark is made by a tire both rotating and slipping on a road. The friction mark doesn't have complete texture as the tire-tread does due to tire sliding or slipping. But the skid-mark still possesses a little outline characteristics as the tire-tread does. Contrarily, scuffmark largely differs from tire-tread. However, skid-mark is mostly happened at accident scene. Thus, how to employ the similarities between tire-mark and tire-tread to identify the belongingness of the tire-mark is an important research issue.

In the literature review, many publications in accident investigation (Baker and Fricke, 1986, Martinez, 1994) gave a detailed descriptions of the causes of tire-marks formation and their outline features for the investigators/policemen to identify the types of marks. A lot of papers were also engaged in the studies of vehicle's speed estimation by using the mark's length or curvature. However, very little has been written on the tire-mark classification. Only, in the newsletter of PARC Views (Lindsay, 1997) once mentioned that in some cases the streaks within skid-marks may be possible to match the pattern of these streaks to an individual tire. But, the author doesn't propose the matching method. Thus, tire-mark matching methods still need to be developed.

This study firstly reviews the influencing factors of the tire-mark formation and then identifies its major and minor factors. Next, a distance-base matching method is proposed according to the similarity between tire-treads and tire-marks. An empirical vehicle-braking test is then conducted to identify the range of changes on the size of tire-mark resulted from the effects of those factors. After that, a matching model is validated by the testing data to recognize the differences of matching results for its empirical application. Finally, conclusions and suggestions are addressed.

2. GEOMETRIC PROPERTIES ON TIRE-MARK

The formation of tire-mark is influenced by many factors such as tire structure, types of tire-tread and materials, environment, vehicle operation condition, etc. Though the geometric-mapping relationship from tire-tread to tire-mark (skid-marks & imprint) is nearly stable, the differences of the size between tire-tread and tire-mark still exist. Its magnitude of the differences depends on the effect of factors mentioned above. Therefore, it is necessary to conduct an empirical car-braking test and thereafter a suitable matching method can be developed and validated based on the testing results.

Because the tire-marks (skid-marks & imprint) were made by tire rolling and sliding, the longitudinal structure (ribs and grooves) on the tire-tread directly demonstrated the layout of tire-marks (such as the arrangement of the streaks and their gaps). Tire's ground-contact area and pressure distribution are key factors to decide the geometric properties of tire-mark. Tire ground-contact area names the footprint area that can directly decide the outline feature and size of tire-mark. Tire pressure distribution on tread can result in different types of tread-wear sliding on the road. In general, the more wear on tread, the more dark of tire-mark on road. The major and minor factors influencing footprint-area and tread-wear on tire-tread are reviewed in the following sections (Veith, 1992, Walters, 1993).

2.1 Tire structure

The composition of tire related to tread-wear includes types of tire (radial-ply、belted bias-ply and bias-ply), groove void fraction on tire-tread, aspect ratio, types of tread patterns tread properties (stiffness or intensity), etc. Tire type is the most significant factor against footprint and tread-wear. The cord-ply of radial tire is constructed by using nylon line or steel wire vertically crossing the central line of tire. Its sidewall employs soft rubber materials whereas tread employs hard rubber materials. It also has more layers than common tire such as the bias-ply tire. Thus, radial-ply tire has high stiffness and its pattern of tread is not easily deformed while contacting the ground. In present, radial tires are mostly used by motor vehicles. On the other hand, the more groove void fraction, the more serious tread-wear and influential layout on the appearance of tire-mark.

2.2 Vehicle operation condition

Vehicle operation condition such as tires' inflation pressure, load, suspension system, type of drive (front-wheel or rear-wheel drive), etc., directly influence tire wear. In general, increased tire loads lead to increased wear. The influence of inflation pressure on tread-wear is not straightforward, whereas on footprint area is much obvious. Lowered inflation pressure increases total footprint-area and tire-deflection as well as changes of interface-pressure-distribution on footprint.

2.3 Environment

Environmental factors related to tread-wear include tire's rubber, pavement (macro- and micro-texture), interface contamination (water, snow, ice) and temperature (tire, air, road), etc. Friction between tire and pavement surface is the most important factor on tire-wear. It depends on the friction coefficient and normal force. Friction coefficient is related to rubber material and pavement characteristics. Rubber with hyper-viscoelasticity can result in abrasive and adhesion wears (Lin, 1998). Two scales of pavement texture are recognized as macro-texture and micro-texture. Micro-texture was a dominant factor in determining tread-wear. Macro-texture played a minor role (Veith, 1992). On the other hand, the magnitude of friction coefficient is influenced by the temperature, tire inflation pressure, and sliding speed. Increasing temperature, tire inflation pressure, and sliding speed lead to slightly increase of the coefficient (Grosch, 1992).

The coefficient on pavement is changeable due to different seasons. From the microscopic views, different sections on road pavement have different friction coefficients. Thus, pavement's effect on tire-wear is dependent on weather and road section. In general, high roughness on pavement frequently resulted in discontinuous striation, fuzzy edges, and inconsistent gray-level on mark. The results frequently increase the difficulties to proceed tire-mark's positioning and measurement.

A tire's footprint area and tread-wear in each car braking are not fixed and uniform due to the direct and combined effects from factors mentioned above. Varieties of tire-mark patterns can be made and their sizes are almost different. Thus, the behavior between tire's normal force and elements' strain is much more complex. It is difficult to predict the changes of widths on tire-mark in real environment by using simulation method such as finite element method (Noor and Tanner, 1985, Chiu and Chen, 2000). This study uses an empirical car-braking test to identify the magnitude/range of variance on the widths of tire marks influenced by key factors. The testing data can then be used to validate the matching method developed and described in the following section.

3. TIRE-MARK MATCHING MODEL

Because the geometric-mapping relationship from tire-tread to tire-mark is influenced by factors mentioned above, the deviation between them is existed. If the magnitudes of deviations on sizes are within acceptable tolerance, a tire-mark can be classified by the similarities between tire-tread and tire-mark (including the widths of elements or ribs and grooves on tread and the corresponding widths of heavy and light streaks on mark). The matching method with theoretical ground and similarity coefficient is described below.

3.1 Theoretical ground

In general, a tire-mark in two-dimension space (road surface) was projected from the tire tread in three-dimensional space. The essential characteristics of projected behavior between them are a two-dimensional transformation due to the tire sliding or rolling on road surface. From matching's view, longitudinal texture on tread is the dominant section to decide the outline feature on tire-mark. The texture of tire-mark is composed of heavy and light streaks. Widths on streaks are important matching data. Thus, if widths on the longitudinal section of tire-tread such as elements' and grooves' distances are changed slightly, while sliding or rolling on road surface, the projected behavior can be reduced to a one-dimensional (widths) transformation. It can be considered as the transformation between the widths of elements and grooves on tread and the corresponding widths of heavy and light streaks on tire-mark as shown in Figure1.

3.2 Similarity index

The width on element or groove is represented by y_i. If a tire-tread has P numbers of width, it can be represented by $(y_1,y_2,\ldots y_p)$. Then, their corresponding width of heavy or light streak on tire-mark represented by x_i, the tire-mark also has P numbers of width represented by $(x_1,x_2, \ldots x_p)$, as shown in Figure 2.

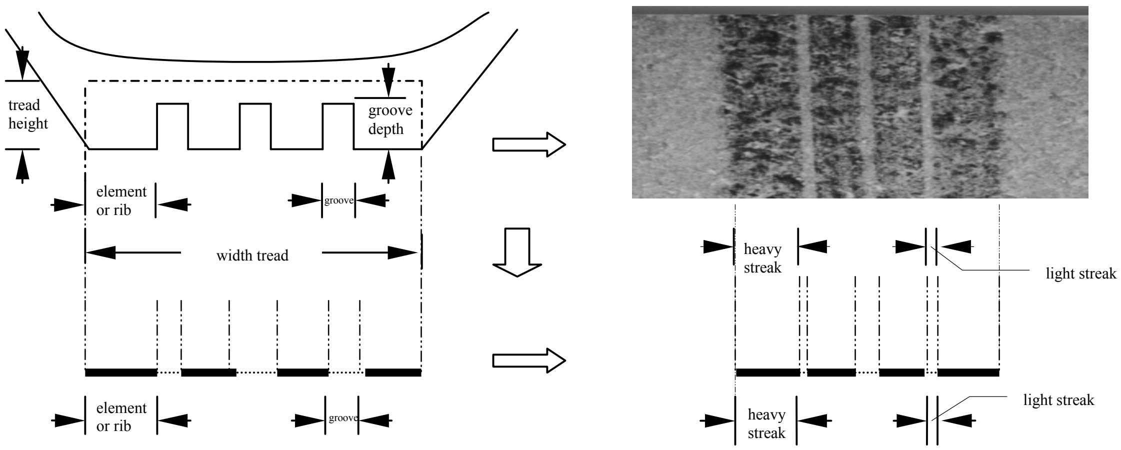

Figure 1 Projection behavior between tire-tread (left) and tire-mark(right)

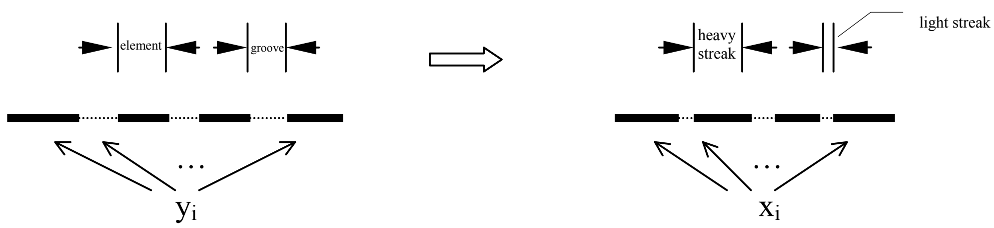

Figure 2 P-dimensional tire-tread and corresponding tire-mark

In order to consider the tire-tread (rubber) with properties of hyper-viscoelasticity and changes of widths on elements and grooves resulted from the effect by non-uniform distribution of contact pressure, the deviation or similarity coefficient between tire-tread and tire-mark can be measured by generalized distance, as shown in Formula (1).

$$d(\mathbf{x},\mathbf{y})=\sqrt{(\mathbf{x}-\mathbf{y})'(\textstyle\sum)^{-1}(\mathbf{x}-\mathbf{y})} \tag{1}$$

where,

$d(\mathbf{x},\mathbf{y})$: a generalized distance between tire-tread and tire-mark.

x_i : i_{th} width of the heavy or light streak on the lateral section of a tire-mark, i=1,2,⋯ p。

y_i : i_{th} width of the element or groove on the lateral section of a tire-tread, i=1…p。

$\mathbf{x}$: $[x_1, x_2, \ldots, x_p]'$: a tire-mark vector composed of widths on heavy and light streaks.

$\mathbf{y}$: $[y_1, y_2, \ldots, y_p]'$: a tire-tread vector composed of widths on elements and grooves.

$\mathbf{\Sigma}^{-1}$: the inverse of variance-covariance matrix $\mathbf{\Sigma}$ of the widths of heavy and light streaks on tire-mark, which can be estimated by the inverse of a sample variance-covariance matrix $\mathbf{S}$.

The P-dimensional matching between tire-tread and tire-mark is dependent on the type of tread-pattern. For example, a tread with one groove and two elements can be matched by their tire-mark with one light streak and two heavy streaks due to their symmetric layout on tire-tread. In the meantime, the value of p is three. However, the value of p is at least equal to one. It means the width of tire-tread is matched by using the width of tire-mark. The situation results from the unclear texture on tire-mark or the irregular pattern of tread. Thus, the similarity index between tire tread and tire-mark can be represented by a generalized distance. A tire-mark can be classified as a tire-tread by using the minimum generalized distance among the matches. Furthermore, if the interaction between the widths on tire-mark is not considered, the covariance between x_i and x_j is equal to zero ($i \neq j$). The Formula (1) can be rewrote as Formula (2).

$$d(\mathbf{x},\mathbf{y}) = \sqrt{\frac{(x_1 - y_1)^2}{S_{11}} + \frac{(x_2 - y_2)^2}{S_{22}} + \cdots + \frac{(x_p - y_p)^2}{S_{pp}}} \quad (2)$$

where,

S_{ii} : the variance of i_{th} width on tire-mark.

other signs denoted as the same in Formula(1).

Finally, if the variance of individual width on a tire-mark is equal, i.e. $S_{11}=S_{22}=\cdots=S_{PP}$, Formula (2) can be rewrote as Formula (3).

$$d(\mathbf{x},\mathbf{y}) = \sqrt{\frac{(x_1 - y_1)^2}{S_{kk}} + \frac{(x_2 - y_2)^2}{S_{kk}} + \cdots + \frac{(x_p - y_p)^2}{S_{kk}}} \quad (3)$$

The generalized distance d($\mathbf{x}$,$\mathbf{y}$) could be substituted by the Euclidean distance when $S_{kk}=1$ ($S_{kk}=(\sum_{i=1}^{P} S_{ii})/P$). In this paper, the three similarity indexes or coefficients will be used to classify the tire-mark data obtained from car braking test and the clustering results will be compared and discussed in detail.

4. CAR BRAKING TEST AND MODEL VALIDATION

In order to identify the variation of widths on tire-mark resulted from the effect by many factors mentioned in section two, a practical car barking test is conducted. The data of tire-mark obtained from the test can then be employed to validate our matching model. The operation procedure for classifying the tire-mark is also introduced in the following sections.

4.1 Description of the car braking test

The purpose of the car test is to identify important influencing factors on the geometric formation of tire-mark and obtain the magnitudes of variations on widths of tire-mark. The test was committed to conduct by the Automotive Research and Testing Center of Taiwan. The test scene was located in Lu-Kung road near the center. In the experiment design, variables include speed (50、70 km/hr), tire inflation pressure (high：46psi、appropriate：36psi、low：26psi), and load (light：1360g、heavy：1520g). The other condition such as the type of tire, driver, vehicle, pavement properties were controlled under the approaching state for decreasing the source of variance. In each mix of the factors' levels, a car was repeatedly braked three times and three observations on tire-mark can be obtained. Thus, the total observations obtained are 35(2*3*2*3-1) where photo of number 509 is failed. Part of tire-marks and their processed images are shown in Figure 3. The test data on tire-marks will be used to identify the important factors among speed, tire inflation pressure, and load and validate the matching method mentioned above.

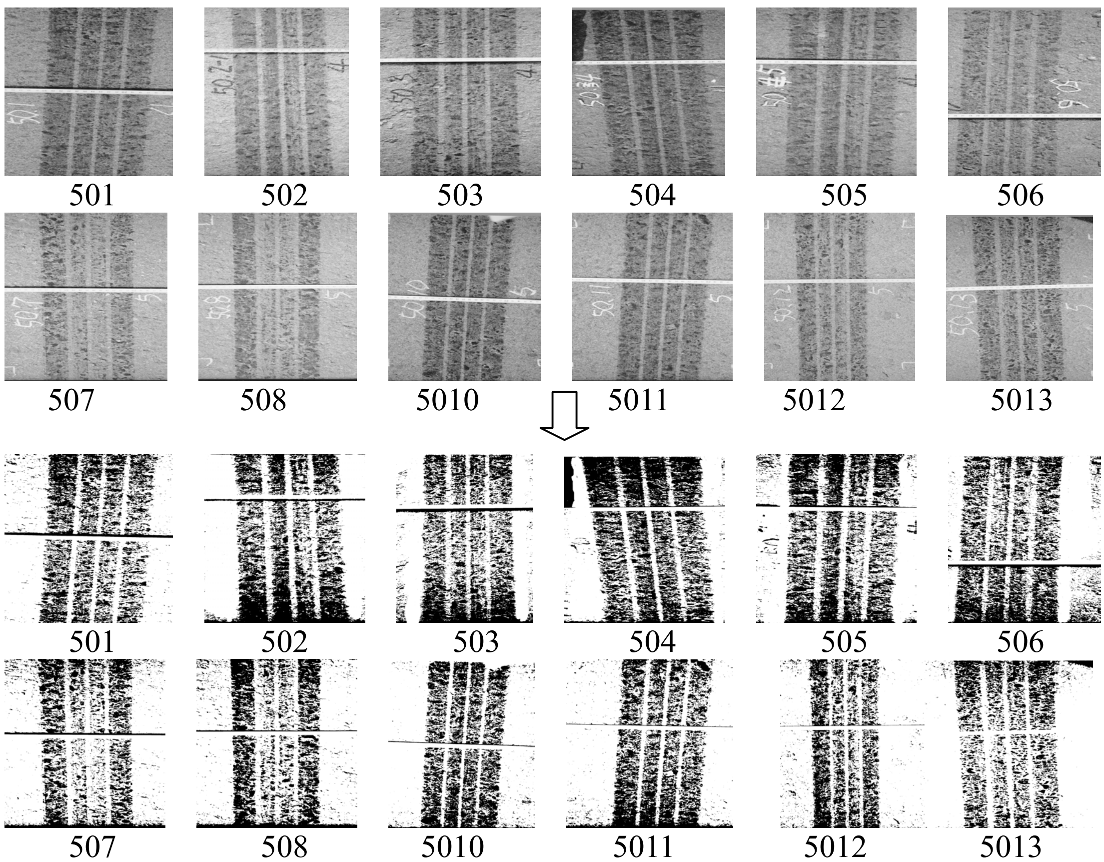

Figure 3 Part of skid-marks and their processed images

4.2 Tire-mark measurements and influencing factor

The measurement of the widths on tire-tread from the first width to the seven width in car braking experiment are 3.45、0.7、2.3、0.8、2.3、0.7、3.45, all at cm, respectively. It can be measured at the scene or out of the scene. The width of the tire-tread is 13.7cm. On the other hand, the widths on tire-mark is not easy to position and measure at scene by human eyes because of the vague edges between heavy and light streaks resulted from fine or slight gray-level changes. However, employing the tire-mark image processed by a simple image-processing method, the clear edges between streaks can be obtained and the positionings and measurements of the widths on it can be easily conducted.

Table 1 The measurements of the heavy and light streaks on tire-marks unit:cm

Braking condition	Photo no.	Total width	Heavy streak 1	Light streak 1	Heavy streak 2	Light streak 2	Heavy streak 3	Light streak 3	Heavy streak 4
50/LL/OI[a]	501	12.89	3.27	0.74	2.28	0.65	2.16	0.79	3.00
	502	12.91	3.24	0.89	2.07	0.83	2.05	0.79	3.03
	503	13.32	3.17	0.91	2.15	0.77	2.17	0.80	3.35
50/LL/AI	504	13.07	3.36	0.73	2.29	0.61	2.24	0.66	3.18
	505	12.58	3.22	0.78	2.12	0.79	1.99	0.81	2.86
	506	13.15	3.33	0.71	2.19	0.69	2.17	0.83	3.23
50/LL/LI	507	13.28	3.48	0.90	2.07	0.81	2.08	0.79	3.15
	508	13.11	3.32	0.84	2.12	0.77	2.12	0.78	3.14
	509	—	—	—	—	—	—	—	—
50/HL[b]/OI	5010	12.79	3.17	0.77	2.24	0.65	2.19	0.72	3.06
	5011	12.84	3.23	0.80	2.19	0.75	2.18	0.75	2.94
	5012	12.68	3.27	0.73	2.14	0.80	1.98	0.80	2.96
50/HL/AI	5013	13.17	3.16	0.94	2.11	0.75	2.16	0.74	3.29
	5014	12.84	3.23	0.81	2.13	0.77	2.02	0.88	3.01
	5015	13.05	3.30	0.83	2.14	0.85	2.07	0.75	3.10
50/HL/LI	5016	13.42	3.21	0.74	2.10	0.77	2.14	0.72	3.73
	5017	13.36	3.56	0.75	2.13	0.75	2.12	0.72	3.33
	5018	13.00	3.42	0.79	2.01	0.74	2.08	0.69	3.19
70/LL/OI	701	13.14	3.12	0.63	2.53	0.62	2.27	0.78	3.37
	702	13.09	3.25	0.65	2.19	0.71	2.25	0.77	3.26
	703	12.91	3.33	0.61	2.31	0.60	2.27	0.74	3.06
70/LL/AI	704	13.39	3.51	0.90	1.95	0.98	2.01	0.80	3.28
	705	13.16	3.17	0.79	2.10	0.81	2.14	0.80	3.35
	706	13.31	3.45	0.76	2.16	0.78	2.16	0.79	3.21
70/LL/LI	707	13.37	3.44	0.88	2.07	0.82	2.00	0.91	3.26
	708	12.90	—	—	—	—	—	—	—
	709	13.21	3.18	1.06	2.06	0.72	2.24	0.64	3.31
70/HL/OI	7010	13.05	3.36	0.71	2.29	0.62	2.27	0.57	3.23
	7011	13.25	3.59	0.71	2.17	0.74	2.17	0.78	3.09
	7012	13.06	3.25	0.72	2.17	0.71	2.21	0.63	3.36
70/HL/AI	7013	13.05	3.42	0.82	2.02	1.01	1.96	0.86	2.96
	7014	13.41	3.79	0.68	2.16	0.71	2.16	0.65	3.26
	7015	13.58	3.76	0.62	2.29	0.64	2.25	0.57	3.45
70/HL/LI	7016	13.67	3.77	0.78	2.05	0.88	2.07	0.71	3.40
	7017	13.20	3.14	0.68	2.14	0.75	2.18	0.66	3.66
	7018	14.04	3.91	0.69	2.10	0.83	2.10	0.72	3.68

Note： a. 70/LL/OI is a braking condition with speed 70km/hr, light load 1360g, over inflation pressure 46psi.
b. HL=heavy load, LL: Light Load, OI=over inflation pressure, AI: appropriate inflation pressure, LI :Lower inflation pressure.

The data of tire-marks obtained from the car test were firstly digitized by the scanner. Then, the tire-marks images, as shown in Figure 3, were processed by a global thresholding method using the average gray-level in the area of tire-mark on a photo. The processed images are shown in Figure 3. The edges between the heavy and light streaks on a tire-mark are much clear.

The number of heavy and light streaks on a tire-mark which resulted from the elements and grooves on tread is four and three, respectively. In order to obtain the widths of heavy and light streaks, the 30 observations on a tire-mark image are randomly selected by human-labor with the pixel-reading program developed. Each observation has the image coordinates of the left and right edge on each width within a tire-mark. Each width on heavy or light streak can be calculated by the deviation of horizontal coordinates in the image coordinate system. Its actual width is estimated by the scale of ruler in a tire-mark image. The measurement results on the 35 tire-marks are shown in Table 1, where photo no.509 is failed and photo no.708 only obtaining its width of tire-mark due to unclear texture.

4.2.1 Influencing factor test

Column 1 and column 3 in Table 1 show us the relationship between the braking condition and the width of a tire-mark. In order to identify the significant influencing factors on the width of a tire-mark, this study use the General Linear Model (GLM) to perform analysis of variance (ANOVA) with unbalanced data which has a missing data on photo no.509. The factors being tested include all one factor such as car speeds (S), tire's inflation pressure (IP), or car load (L), all two-factor interaction such as S*IP, S*L, IP*L, and the three-factor interaction as S*IP*L. The test result is as shown in Table 2. In the significant level of 0.05, the most significant factor among them is the vehicle speed (p value=0.007). Next significant factor is the tire inflation pressure (p value=0.011). The load factor is not significant. Furthermore, the two-factor interaction and three-factor interaction are also not significant factors. This result means that the car speed increased from 50 km/hr to 70km/hr or the tire' inflation pressure decreased from over-inflation to lower-inflation pressure will cause tire-mark's width much broaden. The changes on the other factor or its mix against the effect of tire-mark's width is not significant.

Table 2 Analysis of variance on tire's width (GLM)

Factor	DF	Seq SS	Adj SS	Adj MS	F	P
Speed (S)	1	0.49962	0.45595	0.45595	8.80	0.007
Load (L)	1	0.07725	0.05802	0.05802	1.12	0.301
Inflation pressure (IP)	2	0.56820	0.57380	0.28690	5.53	0.011
S*L	1	0.13157	0.12731	0.12731	2.46	0.131
S*IP	2	0.05769	0.05361	0.02680	0.52	0.603
L*IP	2	0.20372	0.19241	0.09620	1.86	0.179
S*L*IP	2	0.08096	0.08096	0.04048	0.78	0.470
Error	23	1.19218	1.19218	0.05183		
Total	34	2.81120				

Note: DF: degree of freedom, Seq SS= Sequential sums of squares, Adj SS:adjusted Sums of squares, Adj MS: adjusted means squares.

4.3 Similarity coefficient measurement and analysis

The similarity coefficients (SC) between widths on tire-tread and widths on each tire-mark obtained from the car braking test were measured by generalized distance using Formula (1), (2), and (3), respectively. The measurement results are shown in Table 3. The values of SC calculated by Formula (1), show the range between 2.03cm and 9.28cm, and their average and standard deviation are 4.72cm and 1.58cm, respectively. By Formula (2), the values are between 1.86cm and 5.24cm, and their average and standard deviation are 3.41cm and 0.93cm. By Formula (3), the values are between 2.16cm and 5.67cm and their average and standard deviation are 3.81cm and 1.02cm. From the results the similarity coefficients represented by generalized distance (1) have the higher values compared to generalized distance (2) & (3) in average and standard deviation. It implies that the similarity measurement by considering interaction between widths on a tire-mark is more sensitive than none considering the interaction or just considering the individual width variance in survey. The actual matching or classification performance among the three kinds of distances must be further validated by the empirical results of tire-marks clusterings.

Table 3 Similarity coefficients between tire-treads and tire-marks unit:cm

Photo no.	GD 1[a]	GD 2[a]	GD 3[a]
501	5.68	4.11	4.46
502	7.78	4.78	5.26
503	2.36	3.34	3.65
504	5.13	2.56	2.80
505	6.70	5.04	5.56
506	4.59	2.71	3.11
507	3.88	3.36	3.56
508	2.74	3.13	3.24
509	—	—	—
510	5.80	4.82	5.64
511	4.21	4.54	5.63
512	9.28	5.24	5.67
513	3.16	3.03	3.09
514	3.77	4.38	5.01
515	4.33	3.82	4.10
516	4.32	2.87	3.27
517	4.41	3.06	2.93
518	5.36	4.04	3.80
701	4.99	3.02	4.04
702	5.62	2.52	2.55
703	4.83	3.39	4.77
704	3.57	2.87	2.93
705	3.37	1.86	2.16
706	2.14	1.88	2.39
707	3.51	3.38	3.48
708	—	—	—
709	2.03	3.14	4.18
7010	5.24	2.91	3.05
7011	3.90	2.13	3.04
7012	3.76	2.33	2.63
7013	5.12	4.59	4.79
7014	6.09	3.40	3.62
7015	5.98	3.15	3.72
7016	6.09	4.69	4.32
7017	4.10	2.38	2.69
7018	6.77	3.35	4.52
Mean	4.72	3.41	3.81
Standard deviation	1.58	0.93	1.03

Note：a. GD1: the generalized distance calculated by Formula (1),
GD2: the generalized distance calculated by Formula (2),
GD3: the generalized distance calculated by Formula (3).

4.4 Comparison of the classification results

In order to identify and compare the correctness of the tire-marks classified by the three kinds of similarity coefficient, this study employed sample tires as similar to the test tire collected from empirical survey to conduct the task of tire-mark classification. Those tires have different brands, specifications, and tread-patterns. Their actual widths on treads are shown in Table 4. All the tires have three grooves on a tread, which can be used as a basis to perform the classification of tire-marks. Among them, the tire number 5 is a benchmark used in car test. Then, tires are classified into groupings by the k-mean nonhierarchical clustering method using the Euclidean distance between the widths on tread, as shown in Table 5. The centroid is the vector of variable (tread-element or groove width) means for the observations in that cluster and is used as a cluster midpoint. An observation (tire-mark) is classified into a tire-group if its generalized distance to the tire-group centroid is minimum.

To compare the correctness of tire-marks classification, the similarity coefficients are calculated by using the Formula (1), (2), and (3). The measurements based on tires of the five groups are as shown in Table 6. The correctness of classification results on tire-mark of different grouping of tire was compared by three types of generalized distance as shown in Table 7. From the above descriptions of classification results, key conclusions are obtained as below.

(1)In this study, the correctness of classification results on tire-marks by generalized distance (1) is higher than by the generalized distance (2) and (3). It means that interaction between widths on a tread can be measured by the changes of widths on a tire-mark.

(2)The identification rate by generalized distance (1) is much stable than that by generalized distance (2) and (3), while the number of grouping on tire-treads changes. In this study, the appropriate grouping of tires is the five groups which have the highest identification rates calculated by the generalized distances (1).

Table 4 Basic data on the sample tires unit:cm

No.	Brand	Tread-pattern	Specification	Tread width	G_1[a]	W_1[b]	G_2	W_2	G_3	W_3	G_4
1	PIRELLI	P-4000	185/55R1581V	13.5	3	0.9	2.4	0.9	2.4	0.9	3
2	PIRELLI	P-400	185/65R1485T	14.2	3.3	0.9	2.5	0.8	2.5	0.9	3.3
3	PIRELLI	P-2000	185/65R1486T	14	3.2	0.8	2.6	0.7	2.6	0.8	3.2
4	FEDERAL	MS-327	185R14C/8PR.TL	14	3.2	0.9	2.5	0.7	2.5	0.9	3.2
5	BRIDGESTONE	B-381	185/65R1486S	13.7	3.4	0.7	2.3	0.8	2.3	0.7	3.4
6	BRIDGESTONE	V'GRID60	185/60R1380H	16	3.6	0.8	3.1	1	3.1	0.8	3.6
7	BRIDGESTONE	LVR-607	185R14C8PR	13.5	3.4	0.5	2.6	0.4	2.6	0.5	3.4
8	RIKEN	GR-20	185/65R14T	12	2.5	0.9	2.2	0.8	2.2	0.9	2.5
9	KUMHO	Power Max769	185/65R1486H	13.5	2.6	0.9	2.8	0.9	2.8	0.9	2.6
10	MICHELIN	MXT	185/70R1386T	14	3.2	0.9	2.5	0.8	2.5	0.9	3.2
11	MICHELIN	MXTE	185/70R1386T	13.5	3.4	1	1.9	0.8	1.9	1	3.4
12	GOODYEAR	WRANGL ERDT	185R14C	13.5	2.8	1	2.5	0.9	2.5	1	2.8
13	GOODYEAR	EAGLE GA PLUS	185/70R1386H	15	3.3	1.2	2.5	1	2.5	1.2	3.3
14	GOODYEAR	EAGLE NCT3	185/65R1486H	14	3.6	0.8	2.2	0.8	2.2	0.8	3.6
15	GOODYEAR	EAGLE GA PLUS	185/65R1486H	15	3.5	1	2.5	0.9	2.5	1	3.5
16	GOODYEAR	EAGLE GA PLUS	185/60R1482H	15	3.6	0.8	2.7	0.8	2.7	0.8	3.6
17	ELECTRA	STV-128	185/60R1482H	15	4.1	0.5	2.6	0.5	2.6	0.5	4.1

Note: a. G_i: i_{th} element-width on tread.
b. W_i: i_{th} groove-width on tread.

Table 5 The sample tires' grouping

Nos. of grouping / Tire no.	Four [a]	Five	Six	Seven
1	B	E	F	G
2	D	B	C	D
3	D	B	C	E
4	D	B	C	D
5	A	A	A	A
6	C	C	B	B
7	C	C	D	C
8	B	E	F	G
9	B	E	F	G
10	D	B	C	D
11	A	A	A	A
12	B	E	F	G
13	A	D	E	F
14	A	A	A	A
15	A	D	E	F
16	C	C	C	E
17	C	C	D	C

Note: a. Four means the tires are classified into four clusters including cluster A、B、C and D. Each cluster is composed of a lot of tires.

Table 6 Classification results based on the tires with the five groups unit:cm

Group no. / Tire-mark no.	GD 1[a]					GD 2[a]					GD 3[a]				
	A[c]	B	C	D	E	A	B	C	D	E	A	B	C	D	E
501	**7.48**[b]	11.29	13.93	14.14	14.49	5.00	**4.15**	8.97	6.75	6.29	5.49	**4.49**	10.00	6.73	7.11
502	**6.92**	21.64	23.86	31.08	20.05	**4.59**	6.48	11.67	7.34	7.31	**5.35**	5.96	11.78	7.17	7.79
503	**3.64**	7.54	10.69	12.67	11.39	**3.58**	4.73	9.73	6.51	6.92	**4.07**	4.53	9.98	6.58	7.51
504	**6.20**	12.55	13.78	19.94	16.34	**3.99**	4.17	7.28	7.20	6.31	4.33	**3.89**	8.12	7.04	7.38
505	**7.12**	13.61	16.56	18.73	15.88	**5.12**	5.74	10.36	6.53	6.24	**5.81**	5.82	10.97	6.64	6.87
506	**5.10**	11.35	14.30	17.50	15.16	**3.72**	4.89	10.18	7.65	7.56	**4.13**	4.69	9.90	7.60	8.24
507	**4.14**	9.37	11.64	15.51	12.99	**3.17**	4.64	8.56	6.20	6.17	**3.50**	5.03	9.21	6.67	7.44
508	**3.59**	8.13	10.97	14.96	11.93	**3.51**	3.71	8.14	5.95	6.33	**3.63**	4.26	8.82	5.99	6.59
5010	**7.83**	9.63	14.44	13.96	12.67	**6.34**	6.47	13.17	8.38	8.54	7.07	**5.68**	12.85	8.52	8.85
5011	**6.13**	7.13	11.54	10.32	9.85	**5.47**	5.81	11.65	7.30	7.16	6.59	**5.60**	12.17	7.43	7.83
5012	**8.93**	14.10	19.98	17.65	14.42	**5.57**	6.35	11.72	7.95	7.80	**6.04**	6.56	12.27	8.04	8.38
5013	**3.57**	8.91	11.56	13.91	10.98	**3.22**	3.88	7.83	5.25	5.50	**3.38**	3.74	7.94	5.23	5.84
5014	**5.20**	10.14	12.79	17.13	13.57	**4.42**	4.99	9.94	6.20	6.12	**5.15**	5.46	10.96	6.64	7.18
5015	**5.89**	7.84	11.30	11.49	10.47	**4.20**	5.18	9.98	6.78	6.62	**4.53**	5.25	10.53	6.94	7.55
5016	**4.36**	10.26	10.95	14.85	14.04	**3.40**	5.08	7.94	7.38	7.41	**3.66**	5.62	8.32	7.99	8.59
5017	**4.36**	9.12	12.62	13.09	11.90	**3.76**	6.98	11.25	9.74	9.83	**3.64**	6.60	10.60	9.88	10.65
5018	**5.10**	11.44	15.11	15.59	14.12	**4.29**	7.09	12.01	8.64	8.60	**4.37**	6.14	10.98	8.77	9.33
701	**7.31**	14.34	16.54	24.15	19.27	5.27	**5.11**	8.63	8.90	7.68	5.98	**4.58**	10.18	8.44	8.93
702	**6.31**	13.84	19.50	20.36	15.85	3.95	**3.73**	7.95	6.75	6.99	3.87	**3.82**	8.26	6.51	6.90
703	**6.71**	10.87	14.96	17.21	13.97	5.60	**5.56**	9.50	9.46	8.47	6.67	**5.28**	11.04	8.94	9.22
704	**3.17**	8.99	12.71	12.93	10.10	**2.47**	4.36	6.77	5.25	5.27	**2.51**	4.44	7.01	5.4	5.98
705	**3.77**	10.28	12.47	15.97	11.96	**2.08**	2.95	5.64	4.27	3.95	**2.29**	3.11	6.28	4.41	4.84
706	**3.12**	6.24	9.06	10.68	9.69	**2.52**	3.97	7.42	6.10	5.98	**3.12**	4.16	8.13	6.40	7.02
707	**3.90**	8.60	11.55	13.49	14.35	**3.00**	4.82	8.79	6.48	7.75	**2.92**	4.99	8.87	6.36	7.22
709	**3.80**	8.37	10.75	14.74	14.50	**4.09**	4.64	8.51	7.36	7.65	**4.51**	4.83	9.55	6.59	7.35
7010	**6.54**	12.23	14.01	19.24	15.01	**5.07**	5.25	8.82	8.51	7.83	5.08	**4.72**	9.07	8.52	8.80
7011	**3.96**	9.40	10.44	14.85	12.36	**2.86**	4.22	6.81	6.58	6.20	**3.70**	4.53	7.89	6.67	7.19
7012	**5.77**	10.75	13.03	16.41	14.86	**3.86**	5.01	8.85	8.06	7.70	**4.13**	4.99	9.45	8.20	8.58
7013	**5.29**	10.50	14.78	14.91	12.34	**4.11**	6.11	9.82	6.56	6.61	**4.57**	5.80	9.87	6.48	7.07
7014	**6.07**	10.87	14.25	15.46	14.80	**4.10**	6.58	8.25	9.68	9.19	**4.37**	6.58	8.75	9.55	10.09
7015	**6.82**	14.24	15.07	20.33	17.81	**5.54**	7.29	8.60	11.46	10.55	**5.39**	7.72	8.78	12.09	12.62
7016	**5.33**	13.16	16.25	17.15	16.76	**4.31**	8.84	11.63	10.98	11.45	**4.17**	8.08	10.73	10.81	11.72
7017	**5.20**	8.33	10.66	12.94	11.15	**3.23**	4.43	6.65	6.62	6.40	**3.39**	4.56	7.02	6.66	7.01
7018	**5.25**	15.03	15.84	21.62	18.18	**3.71**	6.64	8.34	9.11	8.53	**4.36**	8.05	8.61	10.74	11.53
No. of correctness	34					30					26				

Note: a. GD1: the generalized distance calculated by Formula (1), GD2: the generalized distance calculated by Formula (2), GD3: the generalized distance calculated by Formula (3).
b. Figures with black mark means a tire-mark classified into a group of tires.
c. Group no. A is the benchmark group including the no.5 tire (BRIGESTONE B-381)

Table 7 Correctness comparison of classification results

Numbers of grouping	GD1[a]	GD2[a]	GD3[a]
4	31/34 (91.18%)	14/34 (41.18%)	10/31 (29.41%)
5	34/34 (100%)	30/34 (88.23%)	26/34 (76.47%)
6	33/34 (97.06%)	33/34 (97.00%)	29/34 (85.29%)
7	32/34 (94.11%)	29/34 (85.29%)	26/34 (76.47%)

Note: a.GD1: the generalized distance calculated by Formula (1), GD2: the generalized distance calculated by Formula (2), GD3: the generalized distance calculated by Formula (3).

5. CONCLUSIONS AND SUGGESTIONS

The skid-mark doesn't have the complete texture as the tire-tread does due to the tire's sliding. But it still possesses a little outline features as same as the tire-tread does. The study employed the similarity between tire-tread and tire-mark to perform the task of the tire-mark classification. Because tire has hyper-viscoelasiticity and non-uniformly contact pressure on tire-tread resulted from the effect of factors such as pavement condition, vehicle operation condition, tire structure, etc., the interaction between the widths on tire-tread frequently results in the changes of the widths on a tire-mark. To consider the interaction between the widths on the tire-tread, the generalized distance is used to measure the similarity for the pairs of these items on the tire-tread and their corresponding tire-mark.

The matching method with the similarity index or coefficient is validated by the data of tire-marks obtained from empirical car-braking test. The results show the classification results of tire-marks by using the generalized distance have the high identification rate. Therefore, the research results can be applied and referred by the policemen/investigators in tire-marks investigation and identification. Key conclusions and suggestions are summarized as follows.

(1)In theoretical basis, the three-dimensional mapping from the tire-tread to its tire-mark can be reduced to the one-dimensional mapping from the widths on the tire-tread to the corresponding widths on the tire-mark. Thus, the similarity for the pairs of these widths can be used to classify the tire-mark.

(2)The interaction between the widths on the tire-tread resulted from the effect of the properties of tire's hyper-viscoelasticity and non-uniform distribution of contact pressure on the tread can result in the changes of the widths on the tire-mark. Thus, the similarity between them can be measured by the generalized distance. The validation results on the tire-marks classification show a high identification rate between 91% and 100% in the different groupings.

(3)To identify the important influencing factors on the formation of a tire-mark, an empirical car-braking test is conducted. The results show that the speed and tire's inflation pressure are the significant influencing factors on the width of a tire-mark. The vehicle load is not a significant factor in the situation of increasing the load from the light-load: 1360g to the heavy-load: 1520g.

However, the study must be further improved and developed by the following direction of research.

(1)The practical car-braking test must consider and increase other influencing factors such as the types of tire-tread and material, pavement condition, new and old tires, etc.

(2)The automatically matching method is still an important technique to improve the operation procedure in tire-mark investigation.

(3)A database for tire-mark identification must be established to increase operational efficiency of the vehicle investigation in case of the hit and run accident.

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