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Sustainable traffic safety management at accident black spots combined with drivers’ psychology and vehicle engineering using Eye Mark Recorder

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Abstract

This paper proposes an integrated approach for sustainable traffic safety management at accident blackspots, including a mechanism that tracks the occurrence of accidents from the moment of drivers’ vision to actual accident occurrence, via vehicle behavior. An accident black spot can become a “vicious circle” of accident occurrence and safety countermeasures, where a safety countermeasure is repeatedly performed, but its effect soon fades each time. For such a spot, implementation of a safety countermeasure from only the highway point of view has no sustainability. Therefore, to be effective as one of the next-generation safety countermeasures, the method must integrate considerations from traffic engineering, drivers’ psychology, and vehicle behavior. This paper proposes and discusses a next-generation, integrated traffic safety management method and an explanation of a mechanism that tracks accident occurrence where drivers watch first and then how vehicles behave and lastly what accident risk increases as the series of event.

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Keywords: Traffic safety; sustainability; combination of traffic engineering, driver’s psychology, and vehicle engineering; eye mark recorder;

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1. Introduction

This paper proposes to integrate traffic safety management of traffic engineering, drivers’ psychology, and vehicle engineering to create a safer society in general and specifically at accident black spots.

In traffic accidents in Japan that resulted in fatalities, the number of victims that died within 24 h reached a peak of 16,765 in 1970 and steadily decreased to 8,466 in 1979. Later, however, the number of these fatalities increased and reached a second peak of 11,452 in 1992 (National Police Agency Statistics, 2013). To attain the ultimate objective, i.e., a society with no traffic accidents, the Japanese government has been striving to attain the medium-term objective set in 2003 of “achieving the world’s safest road traffic by reducing the annual number of road traffic fatalities to 5,000 or less, by the end of ten years (Cabinet Office, Government of Japan, 2006).” Therefore, the government established a five-year program, called the Eighth Fundamental Traffic Safety Program, that covers the years from fiscal year (FY) 2006 to FY 2010 and aims to reduce the annual number of fatalities occurring within 24 h of an accident to 5,500 or less by 2008 and to 5,000 or less by 2010 (Cabinet Office, Government of Japan, 2006). Consequently, the annual number of road traffic fatalities was 5,197 in 2008 and 4,922 in 2010 (National Police Agency Statistics, 2013). Their goal was achieved. Henceforth, the Ninth Fundamental Traffic Safety Program, covering five years from FY 2011 to FY 2015, aims to reduce the annual number of fatalities that occur within 24 h of an accident to 3,000 or less by 2015 (Cabinet Office, Government of Japan, 2011). It is more difficult to reduce the number of fatalities from 5,000 to 3,000 or less. Therefore, integrated safety countermeasures that consider traffic engineering processes, drivers’ psychology, and vehicle behavior are very important. ITS and AIS are also important.

In addition, there are black spots where accidents occurred and safety countermeasures were implemented repeatedly in a “vicious circle.” For such accident black spots, a more effective traffic safety program is required. This paper proposes an integrated traffic safety countermeasure that takes into account drivers’ psychology and vehicle engineering. It also studies how accidents occur. The contents of this article are organized as follows: Section 2 proposes the integrated safety countermeasure as one of the next-generation countermeasures. Section 3 briefly reviews the related literature. Section 4 introduces as a case study an accident black spot at the San-noh Corner on Nagoya Expressway in Japan and a short history for implementing safety countermeasures there. Section 5 demonstrates the observed traffic conditions and a sensitivity analysis of centrifugal forces for speed and turning gyration at the corner. Section 6 shows the friction circle of tires and discusses the catastrophe of a series of events as the accident occurrence mechanism. Section 7 demonstrates the driving experiments at the corner using Eye Mark Recorder (EMR). Section 8 presents the conclusions.

2. Literature review

Many researchers have studied accident risks within various states of traffic. Other researchers have employed conflict analysis and methods from other disciplines to study the risk of accidents occurring on highways. Inoue et al. (1978) showed that a single-vehicle accident tends to occur in a noncongested traffic condition, and that a multi-vehicle accident tends to occur in congested traffic conditions of the Hanshin Expressway. They also showed that the accident occurrence rate is higher in congested traffic than in noncongested traffic. Hikosaka and Nakamura (2001) explained the accident occurrence risk by the traffic flow rate and highway capacity for the Tomei Expressway. Oguchi et al. (2004) showed that the accident occurrence risk is higher in a critical traffic state, i.e., a high-density noncongested traffic state, for the Tomei Expressway.

Other studies have proposed methods based on conflict analysis, such as the time-to-collision (TTC) index, post-encroachment-time (PET) index, potential-time-to-collision (PTTC) index, and other indices. Hayward (1972) proposed using the TTC index. TTC is defined as the time to collision if the two vehicles continue to drive at the same speed and in the same direction without any evasive behavior. Allen, Shin, and Cooper (1978) proposed using the PET index. PET is defined as the time from the end of encroachment to the time that the through-going vehicle arrives at the potential point of collision. In other words, the potential site of collision is first determined when Vehicle 1 occupies a certain position at a certain time. PET is defined as the time taken for Vehicle 2 to reach the identified site. Wakabayashi et al. (2003), Wakabayashi and Renge (2003), and Wakabayashi and Muramatsu (2007) proposed using the PTTC index. This is an if-then type of indicator, i.e., if the leading vehicle evades a
dangerous object and decelerates, and if the rear vehicle is following closely in the same lane, then the PTTC is
defined as the rapid evasive actions that the following vehicle needs to take to avoid a collision. The PTTC index is
suitable for high-speed and congested traffic.

Yoshii et al. (2011) analyzed the complex factors, \textit{i.e.}, a traffic-flow factor, a highway geometric design factor,
and an environmental factor, that affect the accident occurrence risk during rear-end collisions, other multi-vehicle
collisions, and collisions with facilities on the side of highways or urban (or intracity) expressways. However, at the
“vicious circle” accident black spots where accidents occur and safety countermeasures are repeatedly performed,
traffic accidents cannot be explained only by traffic factors. At such spots, safety countermeasures should be
performed accompanied by vehicle engineering and traffic psychology supports. There is little study focusing on
this in Japan. Therefore, it was important to combine vehicle engineering and traffic psychology approaches in this
research.

3. Integrating highway, vehicle, and human traffic safety management for sustainable safety

As stated in the Introduction, a depletion effect for traffic safety is expected, because it is more difficult to reduce
a lower number of accident fatalities than a higher number of accident fatalities, \textit{i.e.}, reducing 5,000 occurrences to
3,000 is more difficult than reducing 7,000 occurrences to 5,000. Traffic safety management should integrate
aspects from the highway, vehicle, and human safety management. Conservative and conventional traffic safety
countermeasures have been performed from only one aspect, \textit{i.e.}, by considering safety improvements only for the
highway, vehicles, or other single aspects. However, at the traffic accident black spots, after traffic safety
countermeasures were performed and the number of traffic accidents decreased, soon after the number of traffic
accidents increases again. For such accident black spots, it is important to integrate the scientific findings from
various fields and seek support from these fields, such as traffic engineering, vehicle engineering, and traffic
psychology, to achieve a more effective and sustainable traffic safety measure, as shown in Figure 1. In the next
Chapter, the case study for this idea is introduced.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Three related fields that affect traffic safety}
\end{figure}

4. Accident black spot as case study

The accident black spot chosen for the case study is located on the central ring route of the Nagoya Expressway
in the city of Nagoya in central Japan. Nagoya is located between Tokyo and Osaka. The name of the accident black
spot is San-noh (sharp-curve) Corner and is located on the southwest section of the ring route (shown in Figure 2).
In the curve, lanes were added in August, 2007 by increasing two lanes to three lanes to mitigate usual congestion.
Therefore, while the congestion was resolved, the number of accidents steeply increased on the third lane (right-
most lane). Although traffic safety countermeasures were performed, their effects were temporary (Motegi et al.,
2010). Figure 3 demonstrates the longitudinal transition of the number of accidents and traffic safety
countermeasures from April 2007 to March 2011. The countermeasures were performed in the following three
phases. After the number of lanes was increased from two to three during August 2007, the accident raterapidly
increased. Thus, barrier lines for reducing speed, extensions of the escort line, and a high-intensity reflective sheet were installed as the first phase of safety countermeasures during July 2008. Consequently, the number of accidents initially decreased. Before and after the first phase of countermeasures, the Nagoya Expressway Public Corporation measured the effect of the countermeasures and investigated the factors that led to accidents, such as analyzing changes in accident rates, analyzing changes in driving speeds at the corner, studying the behaviour of risk-taking vehicles by video monitoring, and measuring the skid resistance on the pavement.

However, the number of accidents rapidly increased again, starting in May 2009. At that time, additional safety countermeasures were installed as the second phase improvements with the carriageway marking. For the third
phase of countermeasures, colored resin mortar, mist-grip pavement, and a caution sign-board were installed during September and October 2009. However, the number of accidents on wet pavement sharply increased, starting in May 2011 (Nagoya Expressway et al., 2012).

Figure 3 shows an image of a typical accident occurring at the San-noh Corner just 0.5 seconds before the collision. Driving along the inner lane of the corner causes the vehicle to spin out of control and collide against the inner wall; assuming that the driver’s viewpoint was the essential cause for such an accident. At this corner, many vehicles tend to be driven in the inner lane or the inner shoulder beyond the inner lane markings on the third lane, as shown in Fig. 4. The traffic speed and running passage position on the lane were observed for each lane, and they are reported in Section 5.

At the San-noh Corner, 48 accidents occurred during eight months from April to November, 2008. The accident occurrence rate was 85% and was concentrated near the corner exit of 4.0 kp, where “kp” is a kilometer post of milestone, as shown in Fig. 6 (Nagoya Expressway et al., 2013). The majority of accidents (29) were collisions with road side facilities, as also shown in Fig. 6. Furthermore, during one month, June 2008, 14 similar had accidents occurred, particularly on a wet pavement.

Because this corner is an important part of the central ring route, after an accident occurs, it causes not only loss of human life but also additional accidents, and loss of time for travelers who are stuck in the traffic congestion. Therefore, since an accident causes such damage and loss, effective and sustainable traffic safety measurements is very important.

5. Traffic Speed and Running Passage Position and its Sensitivity Analysis

The traffic speed and running passage position were observed on each lane at the San-noh Corner using video monitoring sampling from 9:00 a.m. to noon on 13 September, 2011. The number of observed vehicles was 5,080. The distribution of speed was calculated from the difference in times between Sections A and C, Sections C and D, and Sections D and E, as shown in Fig. 10. The distribution of running passage positions was collected using six conditions: (1) driving on the inner side beyond the inner lane marking, (2) driving on the inner lane marking, (3) driving near the inner lane marking, (4) driving in the center lane, (5) driving between the center and outer lanes, and (6) driving outside the outer lane markings.

The following results concerning speeds and running passage positions were observed at the San-noh Corner:
5.1. Distribution of Speed and Running Passage Position

1) The speed on the third lane is highest for corner entry speeds (between Sections A and C) and at the midpoint of the corner (between Sections C and D) (See Figures 7, 8, and 10).

2) Vehicles on every lane slowed down in the corner section, and accelerated in the straight section (between Sections D and E) after discharging from the corner. (See Figures 7, 8, and 10).

3) On the third lane, approximately 79% of the vehicles were running on the inner side of the lane at Section C.

4) On the third lane, approximately 33% of the vehicles were running on the inner side beyond the inner lane markings and also on the inner lane marking. (See Figures 9 and 10)

5) On the first and second lanes, many vehicles tended to run in the center lane as compared with the third lane.

5.2. Sensitivity Analysis of Centrifugal Force by Component of Speed and Radius Ingredient

The effect of the increase of risk caused by the increase in speed in the corner and by running inside the corner is evaluated as follows:

The centrifugal force $G$ is given by

$$ G = \frac{mv^2}{r}, \quad (1) $$

where $m$, $v$, and $r$ are mass, speed, and radius. To simplify, let $m = 1$.

Partial differential of Eq. (1) by the component of velocity and inverse radius ingredient gives

$$ \frac{\partial G}{\partial v} = \frac{2v}{r}, \quad (2) $$

and

$$ -\frac{\partial G}{\partial r} = \frac{v^2}{r^2}. \quad (3) $$
Because the unit systems differ, comparison is difficult. Therefore, the equivalent increase in running speed in the corner is calculated from the running speed on the inner side. Thus, evaluation of a traffic safety countermeasure for running the corner can be evaluated.

Although the speed limit is 50 km/h for this corner, many rates of speed are assumed from 50 km/h to 90 km/h, and the vehicle passage radius is given from 90 m to 110 m against the central radius of 100 m. A part of calculation result from Eq. (2) is shown in Table 1. In Table 1, speed is shown in the horizontal direction and the passage radius is shown in the vertical direction.

The centrifugal force is 25.00 at 50 km/h speed and a 100 m radius, 27.04 at 52 km/h and a 100 m radius, and 27.17 at 50 km/h and a 92 m radius. These results suggest that the inner 8 m passage is equivalent to the 2 km/h increase in speed in the same radius at 50 km/h. In addition, centrifugal force is 36.00 at 60 km/h and a 100 m radius, 38.44 at 62 km/h and a 100 m radius, and 38.30 at 60 km/h and a 94 m radius. These results suggest that the inner 6 m passage is equivalent to the 2 km/h increase in speed in the same radius at 60 km/h speed. The sensitivity is approximately 4:1 at 50 km/h and approximately 3:1 at 60 km/h. When the speed is 90 km/h, the sensitivity is approximately 2:1. This indicates that just running inside at a high speed is taking a risk for a slipping accident while cornering. Therefore, not only speed reduction but also prohibiting vehicles from running inside the lane markings is important at the corner.

### Table 1. Sensitivity analysis of centrifugal force by component of speed and radius ingredient

| r(m) | V(km/h) | Speed: 50(km/h) | 52 | ... | 60 | ... | 62 | ... | 70 | ... | 72 | ... | 80 | ... | 82 | ... | 90 | 92 |
|------|---------|----------------|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|
| 90   | 27.78   | 30.04          | ... | 40.00 | 42.71 | ... | 54.44 | 57.60 | ... | 71.11 | 74.71 | ... | 90.00 | 94.04 |
| 92   | 27.17   | 29.39          | ... | 39.13 | 41.78 | ... | 53.26 | 56.35 | ... | 69.57 | 73.09 | ... | 88.04 | 92.00 |
| 94   | 26.60   | 28.77          | ... | 38.30 | 40.89 | ... | 52.13 | 55.15 | ... | 68.09 | 71.53 | ... | 86.17 | 90.04 |
| 96   | 26.04   | 28.17          | ... | 37.50 | 40.04 | ... | 51.04 | 54.00 | ... | 66.67 | 70.04 | ... | 84.38 | 88.17 |
| 98   | 25.51   | 27.59          | ... | 36.73 | 39.22 | ... | 50.00 | 52.90 | ... | 65.31 | 68.61 | ... | 82.65 | 86.37 |
| 100  | 25.00   | 27.04          | ... | 36.00 | 38.44 | ... | 49.00 | 51.84 | ... | 64.00 | 67.24 | ... | 81.90 | 84.64 |
| 102  | 24.51   | 26.51          | ... | 35.29 | 37.69 | ... | 48.04 | 50.82 | ... | 62.75 | 65.92 | ... | 79.41 | 82.98 |
| 104  | 24.04   | 26.00          | ... | 34.62 | 36.96 | ... | 47.12 | 49.85 | ... | 61.54 | 64.65 | ... | 77.88 | 81.38 |
| 106  | 23.58   | 25.51          | ... | 33.96 | 36.26 | ... | 46.23 | 48.91 | ... | 60.38 | 63.43 | ... | 76.42 | 79.85 |
| 108  | 23.15   | 25.04          | ... | 33.33 | 35.59 | ... | 45.37 | 48.00 | ... | 59.26 | 62.26 | ... | 75.00 | 78.37 |
| 110  | 22.73   | 24.58          | ... | 32.73 | 34.95 | ... | 44.55 | 47.13 | ... | 58.18 | 61.13 | ... | 73.64 | 76.95 |

### 6. Friction Circle of Tire and Accident Occurrence Mechanism

The essential mechanism for accident occurrence in highway facilities at corners is the synergy to the catastrophe with three factors of highway geometric design, driver’s reaction, and vehicle behavior. A “friction circle” of tire is the key concept for explaining rational accident occurrence mechanism of these three factors.

The friction circle of tire is that the resultant force between tire and pavement for all directions does not exceed the frictional force \( F_W \), which is the product of vertical load \( W \) and coefficient of friction \( \mu \), and the resultant vector stays within the circle of radius \( \mu W \). The conceptual diagram is shown in Figure 11.

The characteristic of a friction circle of a four-wheeled vehicle is as follows.

\[
F = \mu W g
\]  

(4)  

From Eq. (4), the following General Results (GR) can be made:

- **GR1** The radius of a friction circle becomes smaller as \( \mu \) changes from a dry road surface, to wet road surface, to snowy road surface, and to a frozen road surface.
- **GR2** When the vertical load \( W \) becomes large (or small), the radius of a friction circle will be large (or small). Therefore,
  - **GR3** At the time of acceleration, the radius of the friction circle of the rear wheels increases.
  - **GR4** At the time of braking, the radius of the friction circle of front wheels increases.
  - **GR5** At the time of right (or left) cornering, the radius of the friction circle of the left (or right) wheels increases.
Based on the General Results GR1 to GR5, vehicle behavior (VB) at the limits of cornering is as follows:

- VB1) A drift-out occurs if a front wheel reaches a limit before a rear wheel (Figure 12 (1)).
- VB2) A spin occurs if a rear wheel reaches a limit before a front wheel (Figure 12 (2)).

Therefore, in the case of Behavior VB1, a vehicle will potentially crash into the outside wall first, and in the case of Behavior VB2, a vehicle will potentially crash into the inside wall first. In the accident example shown in Fig. 3, because the road surface was wet and the truck carried no load, the collision was caused by Behavior VB2, and Observations GR1 and GR2 are highly probable.

Next, we consider the driver’s psychology for such vehicle behavior. The centrifugal force increases as speed increases and as the turning radius decreases. Therefore, it is safer to run on the outside of the corner when the corner entry speed is same. However, as shown in Section 5, many vehicles run on the inside of the corner. As stated above, approximately 33% of vehicles ran on the inner side beyond the inner lane marking and on the inner lane marking on the third lane.

Research has studied where drivers look when they steer (Lang and Lee, 1994), but few have studied where drivers steer as they look. From the previously mentioned observations, we assume the following hypotheses of driver’s psychology (DP):

- DP1) A driver looks at the tip inside a curve in order to confirm his or her path.
- DP2) As a result, his or her vehicle runs the inner side of a curve.

If these hypotheses are right, the way the accident in Fig. 3 occurred can be explained in order of Assumption DP1 then Assumption DP2, then Observations GR1, GR2, and GR5, and finally Behavior VB2.

7. Experimental Driving Using Eye Mark Recorder

We proposed a next-generation, integrated traffic safety management method. The ideal and essential safety countermeasure should be performed on the basis of where drivers watch first and then how vehicles behave and lastly what accident risk increases as the series of event. This approach enables the sustainable traffic safety management. Therefore, when driver's fixation point can be controlled, the number of accident at the accident black spots can be reduced. However, quantitative analysis of drivers’ psychology is difficult. Thus the purpose of this experiment is to find the differences in tendencies of fixation points of drivers between before and after navigation using Eye Mark Recorder (EMR) when driving in curve. In this driving experiment, we ask drivers to drive as usual for Phase 1 (“Before” navigation). Then we ask them to drive the center of the lane for Phase 2 (“After” navigation). And drivers’ fixation points are observed by EMR.
EMR is the equipment that records where the participants of experiments are looking at (i.e. fixation points). However, with EMR, we can find only where the driver is looking at, but we cannot find what he/she is watching and thinking. It is a difficult problem in analyzing EMR record. Experimental driving has been performed since 2011 with 27 participants. Here, one case of the experiments performed in December, 2013 and January, 2014 is shown. Figures 13 and 14 show the trace of vehicle before and after the navigation to drive the center of the lane. After the navigation, the meander is reduced. At the same time, Figures 15 and 16 suggest that the distribution of fixation point is rather concentrated into the tip inside the curve before navigation and it is rather decentralize after navigation. The findings are as follows. The hypothesis of DP1 and DP2 that driver’s tendency to look at the tip inside a curve and then vehicle runs inside is confirmed. The safety countermeasures are, for example, to advice drivers to drive the center of the lane or to setting barrier for preventing from inner driving at the corner. This is one of good examples as an expected result, but there are some cases of difficulty in the interpretation.

8. Conclusion

This paper proposed an integrated approach for sustainable traffic safety management at accident blackspots, including a mechanism that tracks the occurrence of accidents from the moment of drivers’ vision to actual accident occurrence, via vehicle behavior. The concluding remarks are as follows:
(1) The safety countermeasure at accident black spots is very difficult from only traffic engineering.
(2) The integrated approach of traffic engineering, vehicle engineering and driver’s psychology is important.
(3) The accident mechanism is discussed using driver’s fixation point, friction circle of tire and vehicle behaviour.
(4) Sets of driver’s fixation point and vehicle behaviour were experimented.
Future Subjects are as followes:
(5) Accumulation of experiment is required.
(6) Additional collaboration with vehicle researchers and psychologist is also needed. One of them is to study the detail of the vehicle behavior as Doi et al., 2013.
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