Use of continuous speed profiles to investigate motorcyclists’ speed choice along exclusive motorcycle lane

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Abstract. The occurrence of speed-related crashes on the exclusive motorcycle lanes in Malaysia is a matter of concern. This study sought to address this concern through the analyses of speed data collected using GPS-based instrumented motorcycles. Consenting motorcycle riders (N = 29) were asked to ride the instrumented motorcycles along a 20 km stretch of an exclusive motorcycle lane along Federal Highway 2 (F02) in the city of Shah Alam. Analyses of the continuous speed profiles revealed significant inputs regarding the exclusive motorcycle lane. The geometric design of the facility is currently allowing motorcyclists to travel with high overall traveling speeds, with frequent and potentially unexpected speed changes. The acceleration profiles on tangents revealed that the motorcyclists were able to reach a cruising speed in only 50.3% of the acceleration trips, whilst other trips were characterized by sudden and rapid changes in speeds. Further, deceleration profiles on tangents indicated that the participants rode onto the transition elements with high approach speeds. The findings of this study highlighted the risk of a crash due to high traveling speeds and large speed reduction, especially during frequent transitions between tangential sections and horizontal curves.

1. Introduction
Exclusive motorcycle lanes have long been introduced in Malaysia to segregate motorcycles from the main traffic and eliminate the risk of collision with the four wheelers. In a study conducted more than ten years ago, the initial construction of exclusive motorcycle lanes was found to be very cost effective with proven success in reducing the numbers of motorcycle crashes and fatalities [1]. However, there is no latest literature that looks into the latest impact of the exclusive motorcycle lanes on crash reduction among motorcyclists. In light of the worrying statistics on motorcycle casualties on Malaysian roads, their segregation from the main traffic should be a priority. Thus, the utilisation of the lane among the motorcyclists should be promoted.

However, many previous studies highlighted one major concern that could affect the safety of the motorcyclists who use the facility; the absence of motorcycle-specific design standards [2–5]. Without the motorcycle-specific design standards, the current design criteria and safety level could not be thoroughly assessed. On the other hand, the occurrence of crashes along the facility has been reported previously. For instance, [6] reported that side-swap collisions and run-off-road single motorcycle...
crashes were the most common type of crashes recorded on the exclusive motorcycle lane along the Federal Route 2 in Shah Alam. [5] discovered that 64.6% of the reported crashes along the exclusive motorcycle lane were run-off-road crashes and crashes involving fixed roadside objects, which could point to the loss of control or unsuitable speed for the prevailing road conditions.

This study set out to investigate the impact of geometric design on the operating speeds along an exclusive motorcycle lane. One way to assess the safety level of a facility is by looking into variability in operating speeds [7,8]. A geometric design that is not in accordance to drivers’ expectation is manifested through a large speed disparity along different segments characterized by sudden speed changes. This lack of consistency in design is postulated to increase the crash rate along a facility [9]. Research on motorcycle operating speeds on the exclusive lane has been mostly restricted to analyses of spot speed data [10]. The experimental work presented in this study provides one of the first investigations into how the operating speeds were affected during tangent to curve transitions. The results could be very beneficial for speed management and engineering treatment of affected sections of the lane.

2. Methodology

Traditionally, the speed distribution of a traffic stream on a particular roadway is measured at a specific location through spot speed studies. The present study aims to improve the depth of spot speed data by using continuous speed profiles, collected along continuous points.

2.1 Instrumentation of the test motorcycle

GPS-based instrumented motorcycles were used to record the operating speeds and riding behaviours of the participants. The main motivation of using the GPS-based instrumented motorcycles was to acquire a database of real-time naturalistic riding data comprising second-by-second speed profiles, thus enabling the analysis of speed disparity along different segments of the lane. The instrumented motorcycles were modified from the original Honda Wave 100 cc models. The motorcycle data acquisition unit (DAQ) was approximately 111.8 mm (W) x 91.4 mm (D) x 25.4 mm (H) in size, weighed around 135 g and powered by 12 V direct voltage. Two weatherproof miniature cameras were used to capture real-time video images of the forward and rear view. A Global Positioning System (GPS) device (update rate: 5 Hz) was used to record participants’ operating speeds. All data were synchronized and stored in a 6 GB memory card. Figure 1 shows the overview of the motorcycle instrumentation. Detailed descriptions of the instrumented motorcycle can be found in [11].
2.2 Location of data collection
Data collection was conducted on a 20 km stretch of an exclusive motorcycle lane along the Federal Highway Route 2, which is one of the longest in Malaysia and recorded the highest motorcycle volume [5]. The average lane width along the selected route was 3.05 m ($SD = 0.16$ m) with the average riding time of 20 minutes. The final dataset consists of speed profile data belonging to 29 consenting participants with an average age of 25.6 years old ($SD = 5.7$), and average riding experience of 7.8 years ($SD = 5.5$). Data collection was conducted in a low volume traffic with good weather and clear visibility to accommodate participants’ free-flow speeds. Participants rode the instrumented motorcycle starting from a petrol station near Batu Tiga toll plaza towards Klang and made a U-turn at an intersection immediately after Sungai Rasau toll plaza, towards the end of data collection point.

2.3 Construction of a database of riding speeds
The continuous speed data and recorded video footage recorded by the instrumented motorcycle were manually examined using a data management software. Any changes in participants’ riding speed were tracked and recorded into a spreadsheet to create a database of a second-by-second speed profile for each participant. During a transition between two or more elements, the final element was considered as such only when the speed stopped increasing or decreasing at the approach point of that element. If the change in speed ended in the middle of a curve, for example, the next element connecting the curve (i.e., a tangent) was recorded as the final element. The corresponding lane geometry data consisting of lane width, length of tangent and radius of selected curves were also added to the database to increase the depth of data analysis. The width of lanes were physically measured on sites, whilst the curve radius and the length of tangent were estimated using Google Earth software. Figure 2 displays the operating speed profile and the instances of speed changes of a participant, on a certain section of the data collection route.

Figure 2. A sample of continuous speed profile and the instances of speed changes
3. Results
Continuous speed profiles involving 1839 speed data were generated for further analysis of acceleration and deceleration behaviours along tangential sections and during transitions between different elements.

3.1 Acceleration profiles on tangents
The speed database was filtered for acceleration events that ended on tangential sections to examine the tangent acceleration profiles. The possibility of participants reaching the cruising speeds on tangents was also examined. Table 1 lists the average acceleration rate, time and distance by groups of final speeds. Out of the total 340 recorded acceleration trips, participants were able to reach the final speeds of a minimum 70 km/h in 82.9% of the trips, indicating a high overall speed distribution on tangents. A cruising speed was defined as the speed that was maintained for a considerable distance by the participant beyond the point of reaching the maximum speed. In other words, the cruising speed is the final desired speeds of an acceleration trip. Only 50.3% of all acceleration trips were the trips where participants reached their cruising speeds on tangents. Other trips were characterized by sudden changes in speeds, whereby the participants had to reduce their speeds rapidly.

| Final speed (km/h) | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 |
|-------------------|-------|-------|-------|-------|--------|
| Number of trips   | 4     | 54    | 134   | 120   | 28     |
| Average acceleration rates (m/s²) | 0.48  | 0.35  | 0.35  | 0.36  | 0.32   |
| Average acceleration time (s)     | 14.5  | 15.7  | 17.8  | 22.6  | 25.7   |
| Average acceleration distance (m) | 120.2 | 112.4 | 138.9 | 195.8 | 275.6  |
| Average initial speed (km/h)      | 32.8  | 49.9  | 54.8  | 59.3  | 64.2   |
| Average speed increase (km)        | 24.3  | 16.7  | 21.4  | 25.6  | 28.9   |
| 85th percentile of final speed (km/h) | 88.0  |

3.2 Deceleration profiles from tangents to transition elements
With high overall speed distribution on tangents, it was found that majority of the deceleration events from tangents to transition elements were initiated from the initial speeds of more than 70 km/h. Table 2 lists the average deceleration rate, time and distance by groups of initial speeds. The average speed reduction across all groups of initial speeds was low and more than 85% of participants managed to ride at 73 km/h after deceleration. These findings could indicate that the majority of participants rode onto the transition elements such as a horizontal curve following the tangents with dangerously high approach speeds.

| Initial speed (km/h) | 30-50 | 50-70 | 70-90 | 90-110 |
|----------------------|-------|-------|-------|--------|
| Number of trips      | 65    | 184   | 432   | 37     |
| Average deceleration rates (m/s²) | 1.57  | 0.71  | 0.75  | 0.95   |
| Average deceleration time (s)     | 2.8   | 6.2   | 7.3   | 7.0    |
| Average deceleration distance (m) | 12.0  | 26.8  | 43.7  | 35.7   |
| Average final speed (km/h)         | 23.9  | 51.6  | 61.5  | 76.8   |
| Average speed decrease (km)         | 14.2  | 12.3  | 17.7  | 16.1   |
| 85th percentile of final speed (km/h) | 73.0  |
Figure 3 displays the speed cumulative frequency distribution plots for the final speeds in acceleration and deceleration profiles on tangents.

![Cumulative frequency distribution plots](image)

**Figure 3.** Speed cumulative frequency distribution plots

### 3.3 Speed profiles during tangent to horizontal curve transitions

The speed change data were normalized with the number of available curves along the route and it was found that the majority of speed changes occurred when participants travelled from tangents to left horizontal curves. There were eight horizontal left curves (LC) along the data collection route. The majority of participants were found to reach their lowest speeds during the transition at the points of curvature (PC) and started to increase their speeds towards the middle of the curve. Table 3 lists the descriptive statistics for the eight horizontal left curves investigated in this study.

**Table 3.** Descriptive statistics for left horizontal curves \((N = 8)\)

| Parameter                        | Mean  | SD    | Median | Minimum | Maximum |
|----------------------------------|-------|-------|--------|---------|---------|
| Curve radius (m)                 | 64.5  | 105.9 | 202.0  | 18.0    | 332.0   |
| Average lane width (m)           | 3.06  | 0.06  | 3.08   | 2.97    | 3.15    |
| Length of preceding tangent (m)  | 806.8 | 429.8 | 650.0  | 384.0   | 1635.0  |
| Initial speed on preceding tangent (km/h) | 77.3  | 8.1   | 77.0   | 50.0    | 97.0    |
| Speed at the beginning of curves (km/h) | 63.1  | 16.5  | 66.5   | 20.0    | 93.0    |
| Speed changes (km/h)             | -14.2 | 15.1  | -11.0  | -59.0   | 14.0    |
| Rate of speed changes \(\text{m/s}^2\) | -0.65 | 0.59  | -0.56  | -4.17   | 0.35    |
| Distance travelled during speed changes (m) | 33.7  | 41.5  | 19.2   | 0.28    | 226.9   |

The speed changes during tangent-to-horizontal curve transitions were found to be overwhelmingly in the form of speed reduction although some data points indicated that participants accelerated through the curves. Table 4 lists the descriptive statistics of speed changes data during tangent-to-horizontal curve transitions.
Table 4. Descriptive statistics of speed changes for individual horizontal left curves

| Site ID | Curve Radius (m) | N of Events | Speed Changes (km/h) | Mean | SD | Minimum | Maximum |
|---------|-----------------|-------------|----------------------|------|----|---------|---------|
| LC1     | 97.0            | 29          | -11.6                | 4.2  |    | -19     | -2      |
| LC2     | 180.0           | 29          | -13.5                | 7.0  |    | -32     | -3      |
| LC3     | 18.0            | 29          | -48.6                | 6.4  |    | -59     | -26     |
| LC4     | 298.0           | 27          | -1.0                 | 5.2  |    | -11     | 14      |
| LC5     | 281.0           | 27          | -2.7                 | 5.0  |    | -13     | 7       |
| LC6     | 256.0           | 29          | -10.8                | 6.3  |    | -23     | 3       |
| LC7     | 202.0           | 29          | -15.2                | 5.7  |    | -29     | -2      |
| LC8     | 332.0           | 29          | -8.5                 | 6.5  |    | -32     | 0       |

Box plots were drawn to examine the distributional characteristics of the speed changes across each individual horizontal curves. Outliers were removed from the dataset prior to the construction of the box plots.

![Figure 4](image)

Figure 4. Speed cumulative frequency distribution plots

Based on the box plots, most speeds reduction were in the range of 0-20 km/h (mean = 14.2 km/h) except for LC3 (mean = -48.6 km/h). In addition, the box plots were comparatively tall (except for LC4), which suggests a large variance in the magnitude of speed changes on individual curves. The large speed disparities could also suggest high inconsistencies in speed changes across participants. Compared to other curves, the biggest reduction in speeds was observed at LC3. Among the horizontal curves, the radius of LC3 was the lowest (i.e., the sharpest curve), which could explain the large mean...
speed reduction. Site inspection indicates that LC3 is located immediately before a petrol station (see Figure 5).

![Figure 5. Location of LC3 on the lane](image)

The researchers postulated that the initial speeds on tangents and the geometric design parameters of the lane could have direct or confounding effects on the magnitude of speed reduction. Thus, an Analysis of Covariance (ANCOVA) test was conducted to examine their relationships, with initial speeds as the covariate. Results of ANCOVA suggested that the initial speeds were significantly related to the variations in speeds during the transition, $F(1, 218) = 41.306, p < 0.001$. Further, when the effects of the initial speed were controlled, the effects of horizontal curves were found to be significant in predicting the speed changes, suggesting that the change in speed can also be explained by the geometry of individual curves, $F(7, 218) = 225.195, p < 0.001$. The homogeneity of variances in speed changes across each curve was confirmed using Levene’s test, $F(7,219) = 1.120, p = 0.351$.

4. Discussion and Recommendations
As mentioned in the literature review, the proven role of the exclusive motorcycle lane in reducing the number of motorcycle crashes should not be left eroded by the increased risk of a crash along the facility. This study set out with the aim of investigating motorcyclists’ speed choice on the lane, focusing on the impact of the lane geometry. The most obvious finding to emerge from the analysis is that motorcycle riders travelled with high overall speeds along tangents and on the approach point during a transition to other elements. Their speed profiles indicate that the change in operating speed occurs frequently and within short travel distance. On top of that, almost half of the acceleration trips were interrupted by sudden and rapid changes in speeds. The speed disparity during tangent-to-horizontal curve transitions was found to be affected significantly by the initial speeds on tangents and the lane geometry. Some of the issues emerging from these findings relate specifically to the risk of a speed-related crash and the need for speed management on the lane. Based on the findings of this study, an introduction of curve-warning signs, accompanied by advisory speed limit signs is strongly recommended at locations where motorcyclists may not be able to judge the safe speed. In addition, traverse bars may be placed before the approach of the transition points along the lane.
5. References

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