Exploring Uncertainties for Crashed Vehicle Travelling Velocity Tolerance in One-Dimensional Crash Configuration

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Abstract: - Evidence suggests that measurement uncertainty is among the most important factors for reliability assessment. Uncertainty plays a vital role in maximising velocity calculation accuracy in crash reconstruction works. It serves as a reliable calculation tolerance, whereby its contribution becomes more significant when the calculated initial velocity is nearly approaching the posted speed limit. The results suggested that damage width and midpoint offset have a low sensitivity of Delta-V from 0.5 km/h to 0.75 km/h for up to 80 cm and 60 cm measurement errors, respectively. For the crush profile variable, a lesser measurement error of 8 cm results in 0.9 km/h deviation in Delta-V. Meanwhile, vehicle mass, drag factor and post-impact displacement have a higher sensitivity of Delta-V, as compared to the two previous variables. The calculation results may deviate from the actual figure for 1 km/h with a missing 75 kg adult occupant. Deviation of almost 2 km/h initial velocity was observed for as low as 0.5 drag factor determination fault. Moreover, with 1 m displacement measurement inaccuracy is also giving rise to the resulting initial speed of 2 km/h. Overall, the principle direction of force recorded the greatest velocity sensitivity among the investigated variables. Within 20° and 45° of inaccurate principle direction of force, the Delta-V deviation increases exponentially, up to 4.25 km/h. The presented findings are beneficial in terms of crash investigator judgment for the thoroughness measurement while conducting the assessment of the crashed vehicle and the crash scene. This investigation will also contribute to enhancing our understanding of tolerance determination for more accurate velocity estimation.

Key-Words: - Crash investigation, crash reconstruction, delta-V, road crash, uncertainty analysis, vehicle travelling velocity

Received: July 25, 2023. Revised: November 16, 2023. Accepted: December 17, 2023. Published: February 28, 2024.

1 Introduction

In-depth crash investigation in principle aims to identify crash occurrence and injury causation factors, accordingly address the recognised problems and prevent reoccurrence in the future. Crash occurrence may be attributed to human [1-2], vehicle [3-4], environment [5-6] or system [7] deficiency. Meanwhile, improper loading [8] or unrestrained occupant [9-10] may lead to injury causation. The thoroughness of examination, especially in conducting measurement may vary between different crash investigators and crash scenes. Limited space and time are regularly identified as common challenges in crash investigation.

During the last few decades, the association between vehicle speed and occupant injury has been at the centre of much attention in road crash discussions. For that reason, vehicle speed is a dominant feature of crash reconstruction. More interestingly, speed data revealed from crash investigation efforts is essential for a wide range of advanced safety assist technology development. Delta-V, the difference between vehicle velocity before and after an impact has a strong relation to occupant injury [11-14]. Recently, it was reported that a successful impact velocity reduction to at least 60 km/h from a higher travelling speed could minimise the probability of occupants from suffering MAIS 3+, significantly [15]. In other words, higher speed is associated with an increased risk of higher injury levels [9,16]. In estimating vehicle speed, the problem is calculated based on damage measurement on the crashed vehicle and marks left on the road environment, indicating pre or post-crash vehicle movement. Damages on vehicle structure reflect energy transferred to the vehicle as a result of a collision impact. Among the evaluated parameters include damage width (*DW*), midpoint offset (*MPO*), vehicle weight (*m*), principle direction of force (PDOF), crush profile (*C1* to *C6*) and vehicle displacement (*s*). These parameters are thoroughly evaluated during a vehicle and crash scene examination.

The measurement accuracy of the said parameters is debatable due to the uncertainty factor. Given this, an allowable amount of variation of the specified quantity should be carefully determined to increase calculation accuracy. Uncertainty in a problem calculation could be associated with assumptions of individual judgment [17] or measurement tools [18]. While calibration minimises the measurement tool inaccuracy, other measurement uncertainties should be carefully determined. Since measurement error is unavoidable as an impact leaves direct and indirect damages, uncertainty analysis is crucial to define the calculation tolerance, especially in determining the crashed vehicle's travelling speed upon impact.

To date, very few published studies have systematically investigated the crashed vehicle speed calculation uncertainty. The primary objective of this paper is to explore uncertainties associated with the speed calculation. This paper has two major elements. First, uncertainty in determining Delta-V. Secondly, uncertainty in estimating vehicle travelling velocity by taking into account the kinematics of the vehicle after an impact. The present work has only considered the context of one-dimensional crash configuration. Therefore, the presented results may not apply to a higher degree of crash configuration problems.

2 Problem Formulation

Understanding the complexity of a crash scenario is vitally important to formulate an appropriate boundary condition. It can be expressed by a complex or a simpler relation of variables, depending on the interpreted scenario and assumptions. In this paper, the number of variables was minimised for better parameter control. In a collision between two vehicles, let the problem occur in the x-axis. The vehicle that hit, denoted as vehicle 1 (*V1*), is moving forward, while the vehicle that being hit, denoted as vehicle 2 (*V2*), is stationary. No movement is assumed in the y-axis and z-axis. Since the crash configuration is considered to happen in a straight line, the crash scenario of both vehicles can be represented as a one-dimensional problem. Fig. 1 illustrates this problem configuration and its notation.

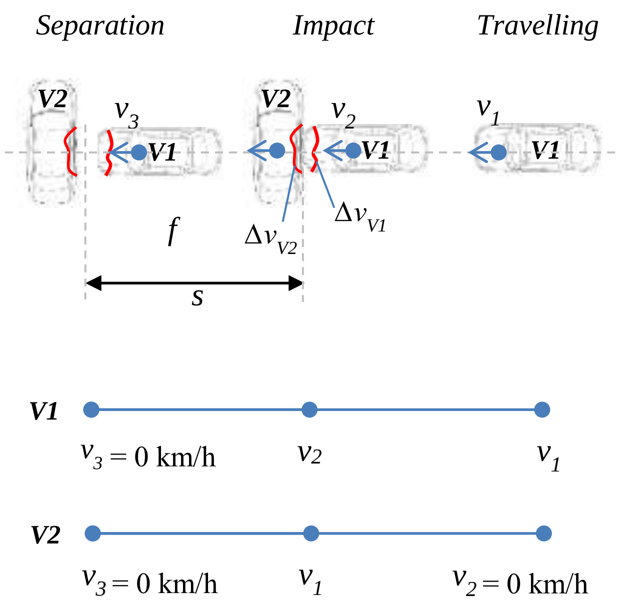


Fig. 1: One-dimensional crash problem configuration and its notation

For such cases, there are three consecutive distinctive events i.e., travelling, impact and separation. The travelling phase is the pre-crash event, in which v_1 is the vehicle travelling velocity just before the impact. Braking and manoeuvring action upon impact are neglected.

The second event is the impact itself, in which *V1* and *V2* collide with each other and move at v_2 after the impact. During this event, the collision impact causes a change in velocity for both vehicles. This velocity changes between pre-collision and post-collision defines Delta-V, Δv of the impact. The Δv experienced by each vehicle can be expressed as in Eq. (1).

$$v_1 - v_2 = \Delta v\,(DW, MPO, m, \text{PDOF}, C1 \text{ to } C6) \qquad (1)$$

where $v_1 > v_2$, $v_2 = 0$ km/h for *V2* and Δv is a function of *DW*, *MPO*, *m*, PDOF and *C1* to *C6*. In most crash reconstruction cases, v_1 of *V1* is the subject of interest as the initial velocity of *V2* is already known.

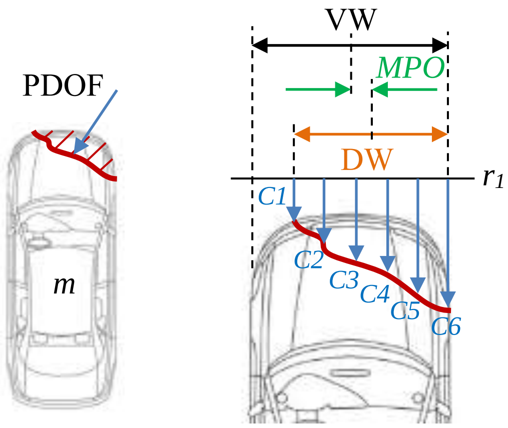
The final event is separation, in which both vehicle was separated, displaced at a certain distance, *s* as a result of the transferred collision energy and finally came to a halt. According to the well-established kinematics equation, this event can be expressed as in Eq. (2).

$$v_3{}^2 = v_2{}^2 + 2\,(fg)s \qquad (2)$$

where v_3 is the final velocity and it is equal to 0 km/h for both *V1* and *V2*, f is the drag factor of the road surface and g is the gravitational acceleration of 9.81 ms^{-2}.

3 Methodology

A crash reconstruction effort requires a physical examination of the crashed vehicle and the crash scene. During the post-crash vehicle examination, there are several variables available for measuring the vehicle damage. Fig. 2 illustrates measurement variables employed in determining Δv, which was calculated using Ai-Damage software [19]. The variables include damage width (*DW*), midpoint offset (*MPO*), vehicle weight (*m*), principle direction of force (PDOF) and crush profile (*C1* to *C6*). Meanwhile, during the crash scene examination, tyre marks, gouge marks and debris are examples of valuable evidence left on the road that assists in determining vehicle trajectory and positioning within the crash events. More importantly, this marking point could indicate the pre-crash and post-crash vehicle displacement (s) that is required in the initial vehicle travelling velocity calculation procedure. It is apparent that the core advantage of this method relies on the evidence-based collected variables.



r_1 = the original frontal vehicle end

VW = the original vehicle width

$MPO = VW/2 - DW/2$

Fig. 2: Vehicle damage assessment variables

Uncertainty analysis was then conducted for each variable to measure its sensitivity on the resulting velocity calculated. For that purpose, a reasonable measurement range was tested and its effect on Delta-V was observed. The reasonable range was determined by taking into account possible measurement errors and crash investigator fault judgment during the physical examination. Furthermore, the sensitivity analysis was also conducted on crash scene variables, by considering a controlled case study. Again, the range was selected based on the lowest and the highest boundary limits of acceptable measurement.

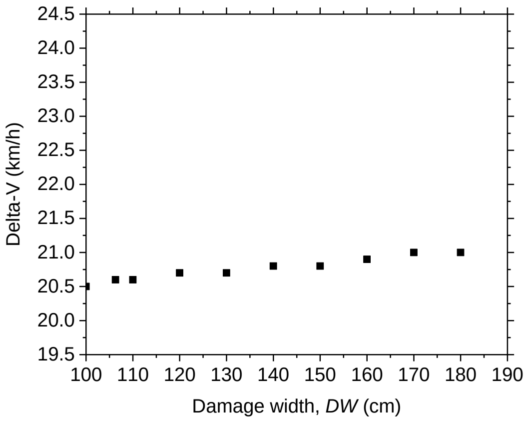
4 Results and Discussion

The findings of this study were structured into the crash investigation physical assessment elements i.e., vehicle damage and crash scene. sensitivity of the calculated speed on the associated variables was presented in the following sections.

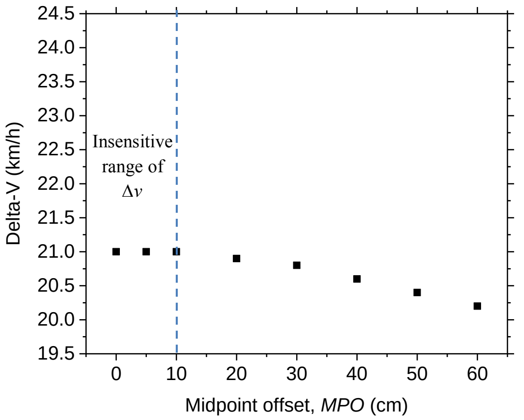
4.1 Effect of Vehicle Damage Assessment on Delta-V

Fig. 3 presents the sensitivity analysis of Delta-V against distance measurement variables i.e., damage width, midpoint offset and crush profile. Referring to Fig. 3(a) for damage width, Delta-V is higher when wider damage width is considered. However, measurement inaccuracy of up to 80 cm results in a Delta-V deviation of less than 0.5 km/h. This range of inaccuracy is possible in measuring damage width as an investigator may include the indirect damage into the measurement due to faulty interpretation of crash opponent transferred paint.

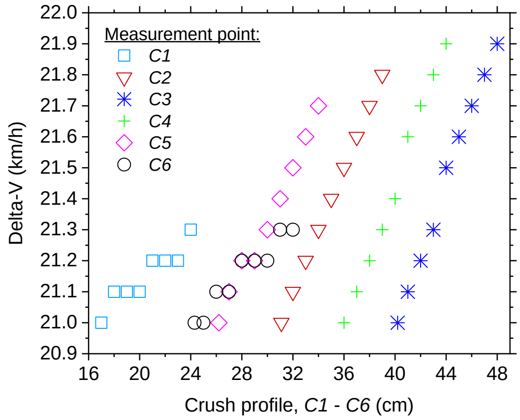
From Fig 3(b), we can see that Delta-V is insensitive to midpoint offset for up to 10 cm. This insensitive range demonstrates that a thorough measurement of damage width which is widely distributed along the vehicle width, leaving about 10 cm undamaged part, is unnecessary. Beyond 10 cm offset, Delta-V is decreasing. Delta-V sensitivity on the larger midpoint offset measurement is slightly higher than the damage width. Variation of midpoint offset of up to 60 cm results in a -0.75 km/h difference in Delta-V. The highest Delta-V was experienced at approximately zero midpoint offset due to the total energy transferred to the assessed impacted area through the vehicle's centre of gravity. In contrast, lower Delta-V was observed at a higher midpoint offset due to energy transferred to other unassessed vehicle structures including indirect damage or the existence of centrifugal displacement as the exerted force did not pass through the vehicle's centre of gravity.



(a)



(b)



(c)

Fig. 3: Delta-V sensitivity on distance measurement: (a) damage width, (b) midpoint offset, (c) crush profile.

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On the other hand, the crush profile revealed a unique sensitivity pattern. It can be seen in Fig.3(c) that up to 8 cm inaccuracy of crush profile measurement, Delta-V showed a very minimal sensitivity of <0.3 km/h, especially at the end of discrete points of crush profile, *C1* and *C6*. Comparatively, Delta-V is more sensitive to the middle crush profile, in the order of *C1*, *C6* < *C2*, *C5* < *C3*, *C4*. In addition, the deeper the crush profile, the more sensitive the resulting Delta-V was observed. Within the tested crush profile range, *C3* which has the highest crush profile of 40 cm results in 0.9 km/h for an 8 cm measurement error. Crush profile measurement error could be attributed to the parallax effect due to the incorrect view position during measurement or incorrect datum line. A datum line represents the original frontal vehicle end for the frontal impact case. It can differ from the original frontal end due to the occurrence of multiple impacts.

Fig. 4 displays Delta-V sensitivity on non-distance measurement i.e., the vehicle weight and the principle direction of force. Referring to Fig. 4(a), Delta-V is inversely proportional to an increase in vehicle mass, similar to the midpoint offset trend.

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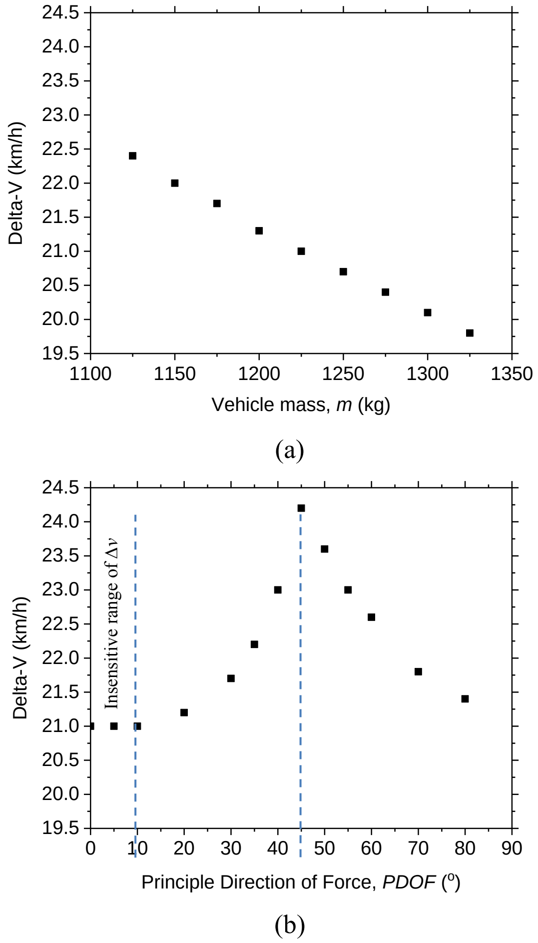

Fig. 4: Delta-V sensitivity on non-distance measurement: (a) vehicle weight, (b) principle direction of force.

In comparison to the damage width and the midpoint offset, a higher Delta-V sensitivity was revealed in response to an inaccurate vehicle mass determined. A missing 75 kg adult occupant in the calculation results in a deviation of 1 km/h Delta-V. Unless details of vehicle occupant data are acquired, this is a very possible missing scenario in crash reconstruction. The main reason would be there is a wide range of diversity of occupant mass but in reality, the average mass is normally assumed.

As shown in Fig. 4(b), false determination of the principle direction of force up to 20º on Delta-V is insignificant (<0.25 km/h). Within 20º and 45º of error, Delta-V deviation increases exponentially up to 4.25 km/h. The Delta-V deviation then decreases, in a negative exponent pattern when the principle direction of force error exceeds 45º. The highest Delta-V deviation resulting from the 45º error is possible if an investigator misinterprets the maximum crush profile as the direction of impact, instead of the vehicle's stiff structure impact position.

4.2 Effect of Crash Scene Examination on Vehicle Travelling Speed

An actual side impact crash test, similar to the configuration presented in Fig. 2 was used as a controlled case study to obtain the acceptable crash scene variables. Fig. 5 depicts the crash scenario at the point of impact and post-impact. Please note that the dotted line refers to the reference line indicating the point of impact and the start of vehicle post-impact displacement, *s* measurement. The post-impact displacement of the vehicle 1 (*V1*) is found to be 8.8 m. For good brake application on a clean and dry paving surface, the drag factor, *f* may range between 0.7 to 0.9 [20]. Since the test laboratory floor is made up of cement, let *f = 0.75.* The crush profile was carefully determined and yielded a Delta-V of 20.7 km/h.

Substituting all the given variables into Eq. (2) produces the *V1* initial travelling velocity, v_1 of 61.7 km/h. In contradiction, the recorded test speed is between 55.87 km/h and 56.06 km/h, as evidenced by the crash test control panel in Fig. 6. To understand the factor of variation between the actual and the calculated speed, the sensitivity analysis of Delta-V is further extended to the crash scene examination variables, which are vehicle displacement and drag factor.

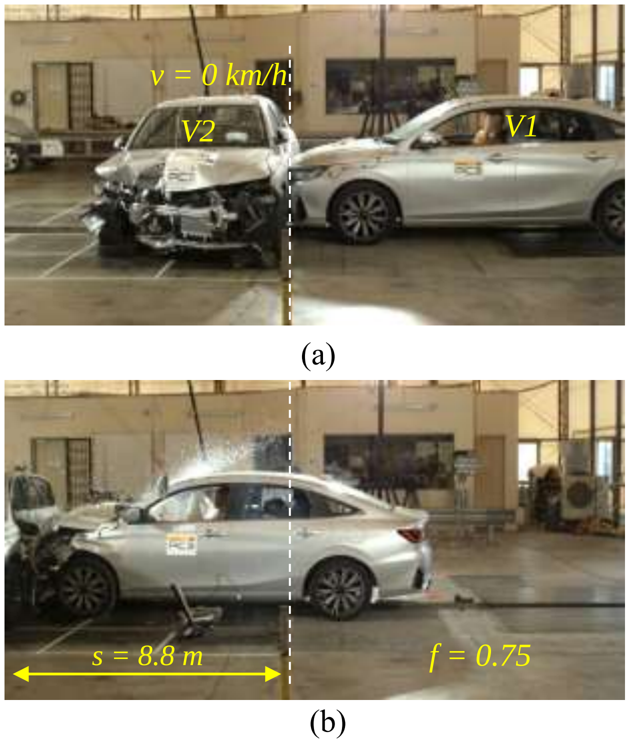

Fig. 5: Controlled case study of a side impact car-to-car crash: (a) at the point of impact, (b) post-impact.

Fig. 7 shows the effect of Delta-V on the variation in the crash scene variables. It can be observed that a positive effect of Delta-V occurred with the association of a higher drag factor. In the case study above, the drag factor is assumed to be 0.75, considering a good brake application on a clean and dry paving surface. Meanwhile, the drag factor of cement may be lower than 0.7. What is surprising is that the drag factor should be as low as 0.55 to obtain the actual speed of ~56 km/h. It is interesting to note that the drag factor variable determination is crucial in estimating the closest speed. Deviation of almost 2 km/h initial velocity was observed for only 0.5 drag factor determination fault.

Fig. 6: Vehicle speed displayed on the crash test control panel

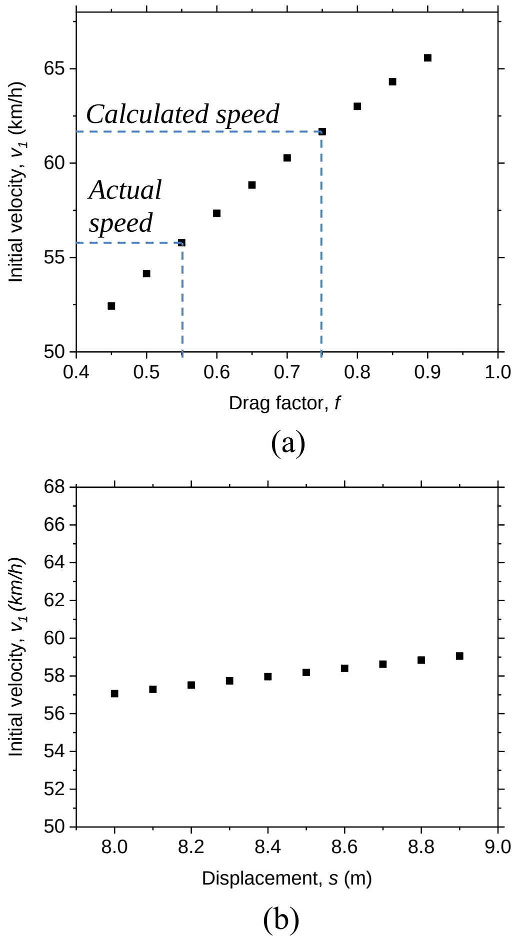

Fig. 7. Delta-V sensitivity on crash scene examination variables: (a) drag factor, (b) vehicle displacement.

Next analysis was carried out on the effect of post-impact vehicle displacement. Fig. 7(b) plots the variation of vehicle initial velocity against the measured vehicle displacement. The graph illustrates that there is an increasing trend of Delta-V as the displacement increases. In the presented case study, this displacement was directly measured based on the displacement from the prescribed impact point and the vehicle's final rest position. Nevertheless, it is a complicated decision in the actual crash cases to determine the exact final rest position. In most of the cases, evidence may have been removed when investigators arrived at the crash scene. Furthermore, current crash investigation practice defines the existence of a gouge mark as the point of impact and debris as the final rest position. However, challenges arise when there are multiple gouge marks on the roadway and massive debris on a wide coverage area.

In dealing with such cases, the determination of both the point of impact and the final rest position may associated with large uncertainties. The uncertainty analysis explains that for up to 0.1 m displacement inaccuracy would result in a deviation of initial speed of ~ 0.2 km/h. What stands out from the figure is the displacement inaccuracy could be multiplied by 10 to 1 m, due to the discussed challenges, giving rise to the resulting initial speed of 2 km/h.

4 Conclusion

The present study was designed to determine the effect of crash investigation variables including damage width, midpoint offset, vehicle weight, principle direction of force, crush profile and vehicle displacement on the calculated pre-impact initial vehicle travelling speed. Based on the discussed findings, it can be inferred that by far the greatest sensitivity is for drag factor and displacement, followed by the principle direction of force, vehicle mass, crush profile, midpoint offset and damage width. The relevance of such uncertainty analysis is clearly supported by the current findings. These data suggest that a verified tolerance can be added to the existing calculation practice to achieve a more accurate result. Although this study focuses on a one-dimensional problem, the findings can be extended to solve higher-dimensional problems. This study provides the first comprehensive assessment of the thoroughness and accuracy level required by a crash investigator in taking measurements in the field.

Acknowledgement:
The authors would like to express their gratitude for the continuous commitment given by the fellow research assistants of the MIROS crash investigation team who have been involved in the crash investigation coordination and data collection.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Fauziana Lamin has carried out the formulation of the problem, organised and executed the related calculation.
The rest of the authors equally contributed to the present research, at all stages from the conceptual framework to the findings and discussion.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This work was supported by the Malaysian Institute of Road Safety Research under grant number VS102202.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.