An inexpensive technical solution for studying vehicle separations within real traffic flows using on-board sensors

J. R. R. Mackenzie[a] and J. K. Dutschke[a]

[a] Centre for Automotive Safety Research, The University of Adelaide

Abstract

Quantifying the separation between vehicles, both laterally and longitudinally, is an important step to understanding some crash events. Examples include, crashes that occur during the various phases of overtaking manoeuvres on high speed roads (pull out, pass, pull in) or where vehicles are passing bicycles on an adjacent travel path. The paper investigates a new option for measuring separation distance using inexpensive LASER distance measuring (LIDAR) devices. Six LIDAR devices were fitted to a vehicle and the accuracy of measurements to another vehicle during an overtaking manoeuvre were evaluated with off-the-shelf differential GPS technology. Data from the LIDAR devices was also used to calculate the passing speed and length of the overtaking vehicle, and the accuracy of these calculations was evaluated. Preliminary results show that the setup delivers results that are acceptable up to distances of 50 meters and at passing speeds up to 20 km/h. This inexpensive solution will facilitate research where separation distance in real traffic flow is an important consideration. Effective use of the technology should take into account possible weaknesses such as inaccurate device positioning and the potential for spurious data.

Introduction

Separation distance has been identified as a crucial factor in several types of crash. For example, Sun and Ioannou (1995) explored the relationship between longitudinal separation and the risk of a rear end collision. It was discovered that, along with other parameters such as reaction time and braking capability, the separation distance between the leading and lagging vehicles plays an important role in determining rear end collision severity.

Lateral separation is also a consideration in crash risk, especially for high speed rural roads. The width of lanes, centre medians, and roadside shoulders will affect the lateral separation between vehicles as well as to roadside objects like trees and poles. Garner and Deen (1972) discovered that as median width decreased, crash frequency increased. Similarly, an analysis of the effect of lane width and shoulder width by Gross and Jovanis (2007) found that, in general, crash rate increased as width decreased.

Another area where lateral separation distance has been a consideration is in vehicle-bicycle overtaking. If the lateral distance between a cyclist and a passing vehicle is too small a collision can occur. Research has shown that crashes resulting from a vehicle passing a cyclist too closely are more likely to result in severe injuries compared to other types of crash between cyclists and vehicle (Stone and Broughton, 2003). Even without a physical collision, the mere sensation of being passed by a vehicle too closely has been identified as one of the most uncomfortable experiences for a cyclist which can lead to instability and a fall (Guthrie et al., 2001; Parkin et al., 2007; Heesch et al., 2011). In light of this, Haworth & Schramm (2014) conducted a review of the literature on vehicle-bicycle passing distance studies and noted that further research is required to investigate what an appropriate minimum passing distance may be and whether drivers would be able to correctly judge this distance accurately.

Previous efforts to study separation distance in real traffic flows have made use of ultrasonic sensors (e.g. Walker et al., 2014) and video analysis (e.g. Parkin and Meyers, 2010). However, both

of these technologies have limitations. Ultrasonic sensors are usually limited in range to just a few metres and have a cone shaped detection area which makes it difficult to locate objects precisely. Automatic video analysis can be useful but is also limited in range (accuracy per pixel degrades at distances greater than a few metres) and may require complex software to be developed (Ponte et al., 2014). The requirement for complex software can be overcome with human analysis but can be costly if large amounts of video require manual processing.

This paper investigates a new method of measuring separation distance with an inexpensive LIDAR device that claims accurate measurements (within 2.5 cm) up to a maximum of 40 metres. The potential for using the LIDAR device to measure separation distances and a validation of the accuracy during an experiment designed to emulate a real traffic environment is presented below.

Materials

LIDAR operates by emitting a laser beam towards a surface and analysing the light that is reflected back. The distance to the surface is calculated by precisely measuring the time between when the laser beam is emitted and returned. Some LIDAR units utilise rotating mirrors to scan the laser beam back and forth to build up a two dimensional matrix of distance data.

Because of the precise timing electronics, rotating mirrors, and optics, LIDAR units are usually expensive and applied to specific tasks such as 3D surveying or accurate machine control. However, an inexpensive module, aimed at hobbyists, has recently come to market (Pulsed Light 3D, 2015). This module, called the LIDAR Lite, is shown in Figure 1.

A microcontroller is used to request a distance reading from the LIDAR Lite module. The module then attempts to determine the distance to an object in its beam path. If successful, the distance is returned to the microcontroller. If the reading fails, for whatever reason, then a zero is returned to indicate an unsuccessful reading.

Note that the LIDAR Lite module is classified as a class 1 LASER and is not harmful if accidently directed into a person's eyes.

Method

A Subaru Impreza was fitted with six LIDAR Lite modules. Two were mounted facing towards the front, two facing the rear, and two facing the right side as shown in Figure 1. The LIDAR modules were positioned and directed such that they would detect a typical vehicle travelling within their targeted zones. The rear LIDAR modules were mounted either side of the licence plate so that they would likely detect the front bumper (or bonnet leading edge) of a vehicle travelling behind. The side LIDAR modules were mounted to the right side wheel wells and directed slightly upwards so that they would detect the side of any vehicle that passed within a few metres. The front LIDAR modules were mounted similarly to the rear modules on either side of the licence plate where they would likely detect the rear bumper (or boot) of a vehicle travelling ahead.

The six LIDAR modules were connected to a microcontroller which was programmed to cycle as fast as possible through each module and request a distance reading. To improve the resolution of the overtaking speed estimate (see below), distances were requested from the side LIDAR modules twice per cycle. This resulted in eight readings during each cycle.

The total cycle time varied as the speed with which each LIDAR returned a reading (or determined that no reading was possible) differed depending on the circumstances at the time. However, a time of less than 273 ms was observed for 90 per cent of the cycles during the testing described below. For the side LIDAR modules this equates to a typical cycle time of less than 137 ms.

A faster cycle time can be achieved by using less LIDAR modules. The cycle time can also be reduced by increasing the communication rate between the microcontroller and LIDAR modules. However, this must be performed carefully as it can result in communication errors and invalid data.

Figure 1. LIDAR Lite module and mounting locations during testing
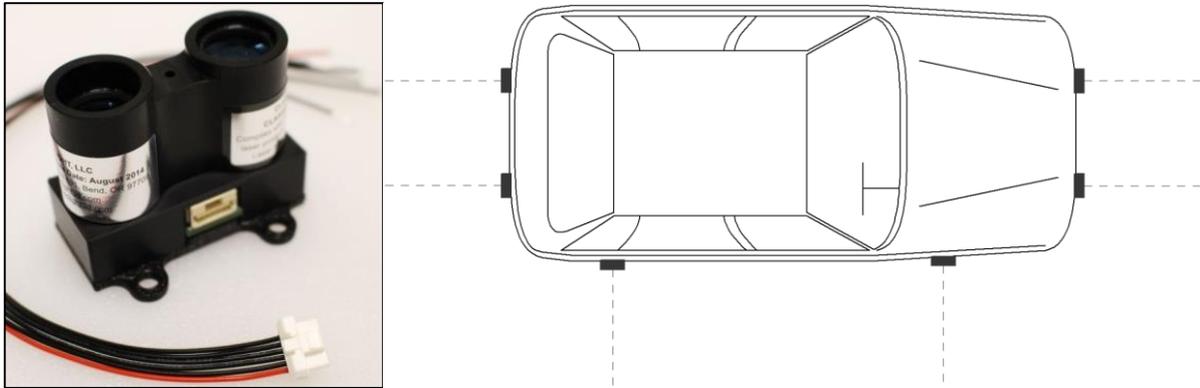
An overtaking test manoeuvre was used to investigate the data collected by the LIDAR modules. The subject vehicle, fitted with the LIDAR modules, was driven at a constant speed of approximately 60 km/h along a relatively straight section of road. Another vehicle (a Subaru Outback, referred to hereafter as the passing vehicle) then approached the subject vehicle from behind, pulled out, passed at a speed of around 70 - 80 km/h, pulled back in, and continued on for a few more seconds at which point the test was halted. This overtaking manoeuvre was repeated 18 times while the data from each LIDAR module was being recorded. No other vehicles were present on the road at any point during the tests.

To validate the data from the LIDAR modules, and evaluate their accuracy, a Racelogic Vbox dual antenna GPS system (Racelogic, 2015) was installed in both the subject vehicle and passing vehicle. The two Vbox systems are able to communicate in real time to continuously monitor and log the position of the passing vehicle relative to the subject vehicle with a claimed accuracy of better than 2 cm.

The microcontroller connected to the LIDAR modules was also connected to the subject vehicle Vbox system. All of the returned distance readings were transmitted to the Vbox such that they would be logged concurrently with the Vbox GPS positional data and facilitate a side by side comparison.

The data obtained from the front and rear mounted LIDAR modules were filtered to remove readings that were obviously spurious. Any group of sequential distance readings that were not sustained over a period of 0.8 seconds (before an invalid zero reading was returned) were deemed to be spurious and set to zero.

While each individual LIDAR module can detect distance, they can also be used in pairs to determine other relevant factors. For example, if the speed of the subject vehicle is also known (e.g. via a GPS system), then the time difference between detections from the pair of side LIDAR modules can be used to calculate the average overtaking speed. Furthermore, the duration of detection by the side mounted LIDAR modules can used to calculate the length of the overtaking vehicle.

The speed of the overtaking vehicle (s_o) can be calculated as shown in Equation 1, where s_s is the speed of the subject vehicle, d is the longitudinal distance between the front and rear LIDAR

modules, t_f is the event time at the front LIDAR module, and t_r is the event time at the rear LIDAR module. An event can be noted as either the vehicle entering (rising edge) or the vehicle leaving (falling edge) the LIDAR module detection zone. The average of the two speeds calculated using the rising edge and falling edge was considered the most appropriate value to report.

Equation 1. Speed of overtaking vehicle

$$s_o = s_s + \frac{d}{t_f - t_r}$$

The length of passing vehicle (l_p) can be calculated as shown in Equation 2, where s_o is the speed of the passing (calculated above), $t_{1 \to 0}$ is the rising edge time of a LIDAR module detection event, and $t_{0 \to 1}$ is the falling edge time of a LIDAR module detection event. A calculation can be made using data from either the front or rear LIDAR module. The average of the lengths calculated using both the front and rear module, along with the average passing speed, was considered the most appropriate value to report.

Equation 2. Length of overtaking vehicle

$$l_p = s_o \times (t_{1 \to 0} - t_{0 \to 1})$$

The accuracy of these calculations will be affected by the cycle time of the LIDAR/microcontroller system. A faster cycle time will increase the accuracy and a slower cycle time will decrease the accuracy. The accuracy of Equation 2 is particularly affected by the cycle time as it relies on a previous calculation from Equation 1.

The Results section below will present a comparison of the data obtained from the LIDAR modules to the data collected by the Vbox systems.

Results

An example of the data collected by the LIDAR modules during one overtaking manoeuvre is shown in Figure 2. The figure is split into two with data from the LIDAR modules located in a longitudinal (front/rear) direction in the upper graph and data from the lateral (side) direction in the lower graph. Note that the rear left LIDAR module was discovered to be misaligned and thus did not capture any data during this test run. Also shown in Figure 2 is the corresponding longitudinal and lateral data recorded by the Vbox system. The Vbox lateral data is defined as the distance between the longitudinal centrelines of each vehicle. A second line that has been adjusted to compensate for the width of each vehicle, so as to display the distance between the side of one vehicle to the side of the other, is also shown.

Over the course of the test run the following points of interest can be observed:

- Point A - The passing vehicle approaches the rear of the subject vehicle and is detected by the right rear LIDAR module from a distance of approximately 45 metres to 20 metres.

- Point B - The passing vehicle is un-detected as it moves to the right and begins the overtaking manoeuvre.

- Point C - As the passing vehicle comes alongside the subject vehicle it is detected by the side mounted LIDAR modules; firstly the side rear and then the side front. The distance data varies by up to two metres (possibly due to reflections between the vehicles) but for

use with Equation 1 and Equation 2 only the passing vehicle's detection time and un-detection time is crucial.

- Point D - The passing vehicle un-detected again as it travels past the subject vehicle.

- Point E - The front mounted LIDAR modules detect the passing vehicle as it begins to move back into the correct lane, in front of the subject vehicle. As the passing vehicle returns to the correct lane it is detected first by the front right LIDAR module (at a distance of approximately 15 metres) and then the front left LIDAR module (at a distance of approximately 18 metres). The front LIDAR modules continue to track the longitudinal range of the passing vehicle up to a maximum distance of approximately 30 metres, at which point the test is halted.

Some spurious readings from the front right LIDAR module, which were not removed by the cleansing process described earlier, can be observed towards the end of the overtaking manoeuvre. The frequency of such readings is explored below.

The data from the side mounted LIDAR modules has been restricted to distances of less than six metres to eliminate irrelevant readings picked up from distant roadside objects.

The subsections below utilise the aggregated data from all 18 runs through the overtaking manoeuvre to explore various aspects of the LIDAR module's suitability as an on-board separation distance measurement device.

Figure 2. Data obtained from LIDAR modules during a single run of the overtaking manoeuvre (see text for points of interest)
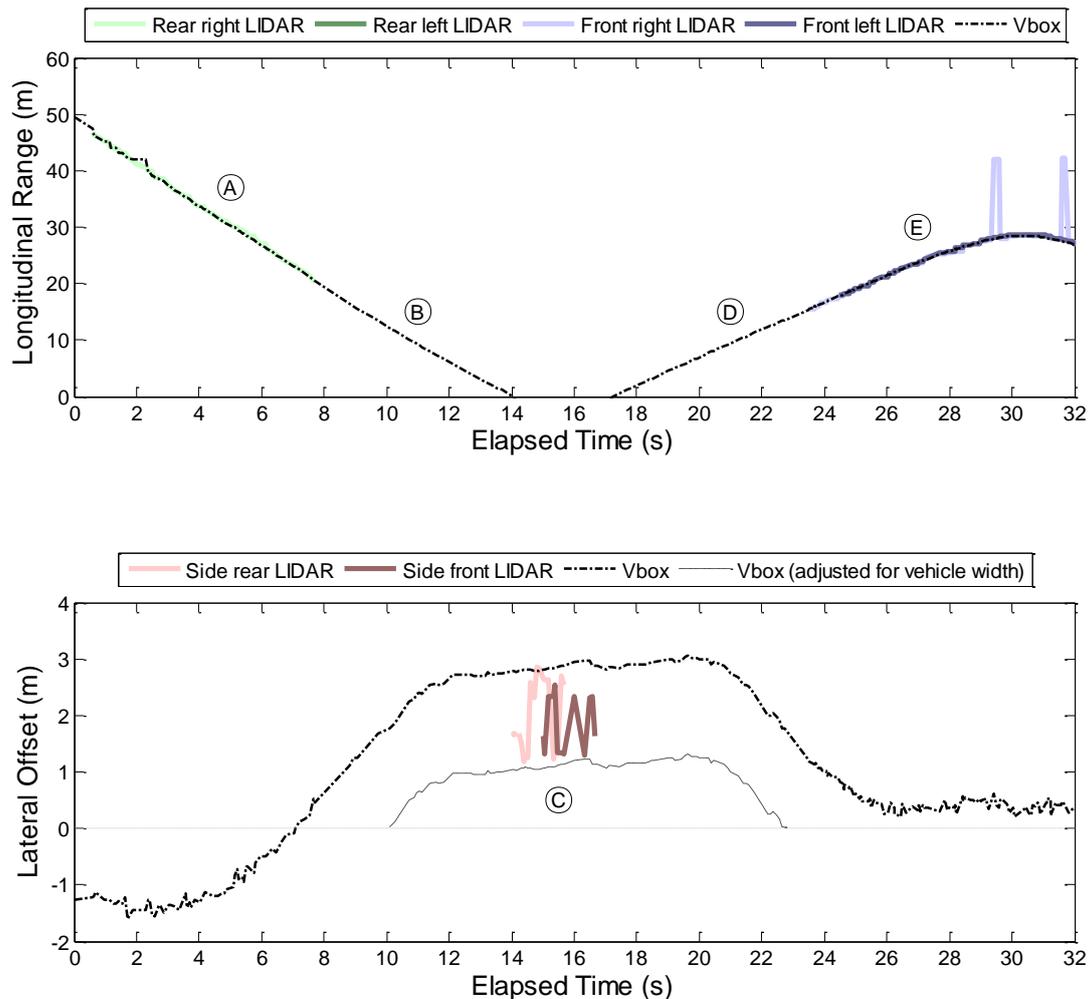
Lateral distance

The side mounted LIDAR modules were positioned low down on the subject vehicle and angled slightly upwards. This upwards angle was to ensure that some point of the passing vehicle would be detected by the LIDAR modules during overtaking. If the LIDAR modules were horizontally aligned, they may only have detected the wheels of passing vehicles or nothing at all. Because of the angled alignment the side LIDAR modules were not able to measure lateral distance and no comparison to the Vbox data was made.

Longitudinal distance

The Vbox data was used to determine when the passing vehicle was directly behind or ahead of the subject vehicle and within a distance that it should be detectable by either the rear or front mounted LIDAR modules. More specifically, when there was a lateral offset of less than ± 1 metre and a longitudinal range of less than 50 metres between the passing and subject vehicles. If the passing vehicle was behind it was defined as being in the rear detection zone, and similarly for the front detection zone when the passing vehicle was ahead.

There were 1,524 readings requested while the passing vehicle was within the rear detection zone. The rear LIDAR modules returned a non-zero (i.e. valid) result for 53.8 per cent of these requests. The front LIDAR modules returned a non-zero result for 93.4 per cent of the 992 readings requested

while the passing vehicle was within the front detection zone. The higher error rate for the rear mounted LIDAR modules was likely caused by the greater number of readings that were requested at long range, where small misalignments are made worse. A significant misalignment of the rear left LIDAR module was also discovered during testing. Further investigation found that the rear left LIDAR module returned a zero for 63.9 per cent of requested readings, compared to 28.5 per cent for the rear right LIDAR module.

Figure 3 compares the non-zero readings for the rear and front mounted LIDAR modules to the Vbox longitudinal range while the passing vehicle was within the rear and front detection zones. Analysis of the data found that the mean error between the rear LIDAR readings and the Vbox longitudinal range was -0.4 metres, with a 90th percentile spread of 1.3 metres. For the front LIDAR modules the mean error was also -0.4 metres, with a 90th percentile spread of 1.2 metres.

Figure 3. Non-zero LIDAR readings while passing vehicle in the rear and front detection zones, compared with Vbox longitudinal range
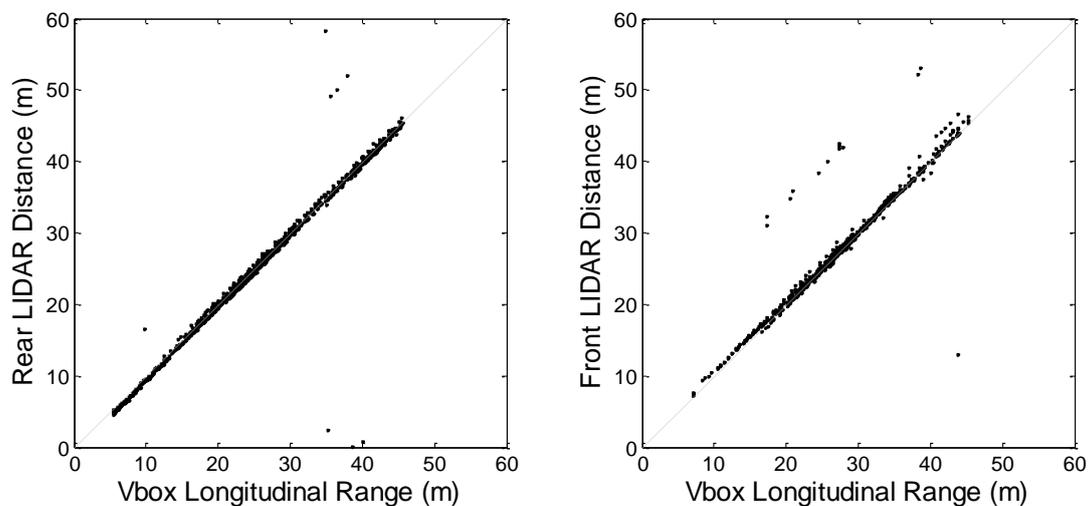
Passing vehicle speed

Using Equation 1, the speed of the passing vehicle as it travelled past the subject vehicle was calculated for each of the 18 overtaking manoeuvre runs. Passing speed was calculated using both rising edge detection and falling edge detection. Figure 4 shows the calculated speeds compared to the Vbox average passing speed. The cycle time during each measurement was used to determine upper and lower limits for each calculation which are shown as error bars.

It can be observed that the potential for error increases as passing speed increases. Greater accuracy may be achieved by reducing the cycle time in applications where determining passing speed is deemed to be important.

In the lower half of Figure 4 the average of the rising and falling edge calculations is shown plotted against the Vbox average passing speed. Lines showing an error of ± 2 km/h have also been plotted, showing that all but one of the averaged calculations lay within this zone.

Figure 4. Calculated passing speed based on rising edge, falling edge, and averaged, compared with Vbox average passing speed
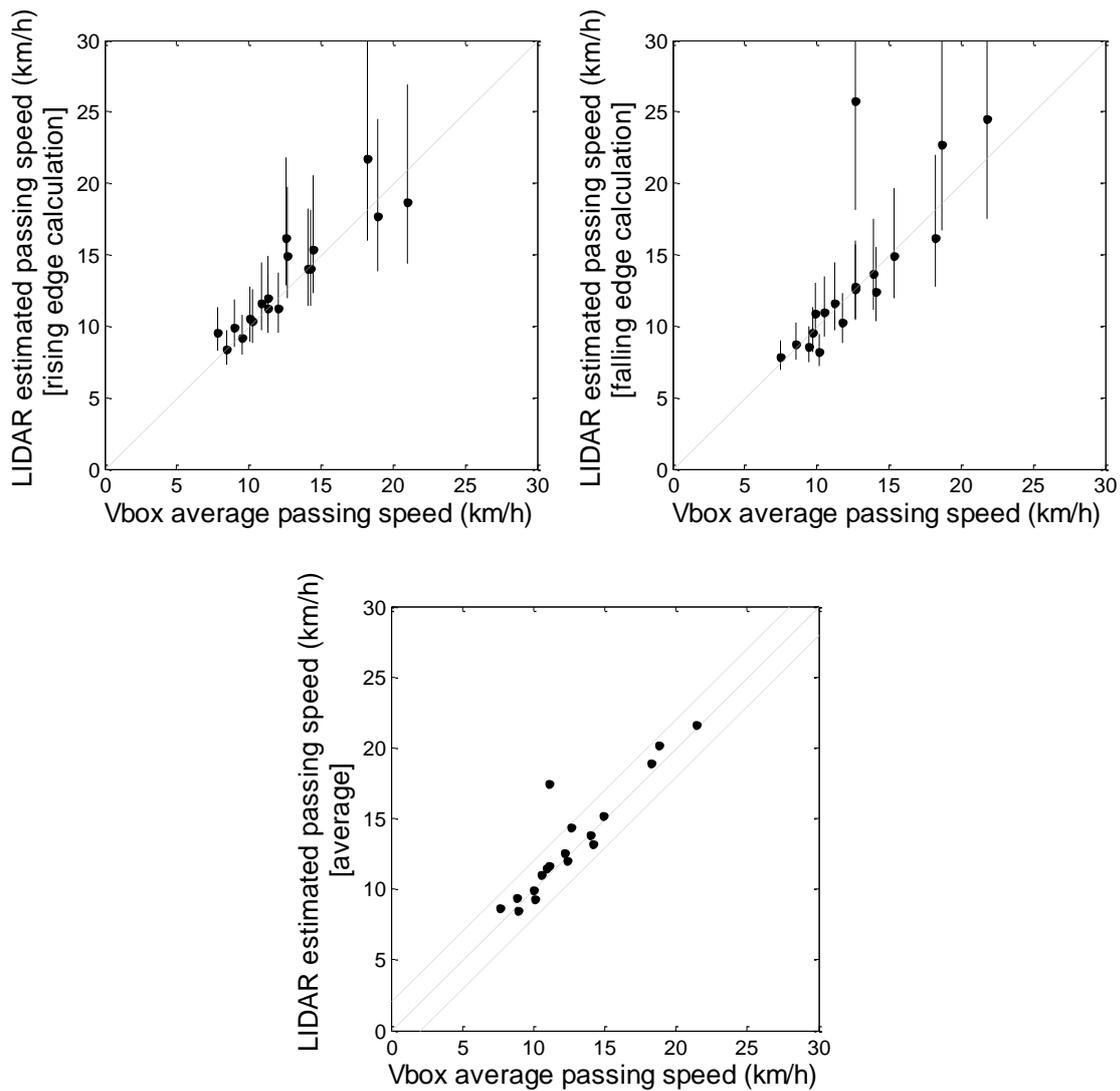
Passing vehicle length

Equation 2 was used to calculate the length of the passing vehicle based on the data from the side mounted LIDAR modules during the 18 overtaking manoeuvres. A separate calculation was made using both the rear LIDAR module and the front LIDAR module. The results of these calculations are shown in Figure 5 and compared to the manufacturer specified passing vehicle length of 4595 mm. The cycle time during each measurement was used to determine upper and lower limits for each calculation which are shown as error bars.

In the lower half of Figure 5 the average of the rear and front LIDAR module calculations is shown compared against the manufacturer specified vehicle length. Lines showing an error of ± 1 m have also been plotted, showing that all but one of the averaged calculations lay within this zone.

Figure 5. Calculated passing vehicle length based on rear LIDAR data, front LIDAR data, and averaged, with a comparison to manufacturer specific vehicle length
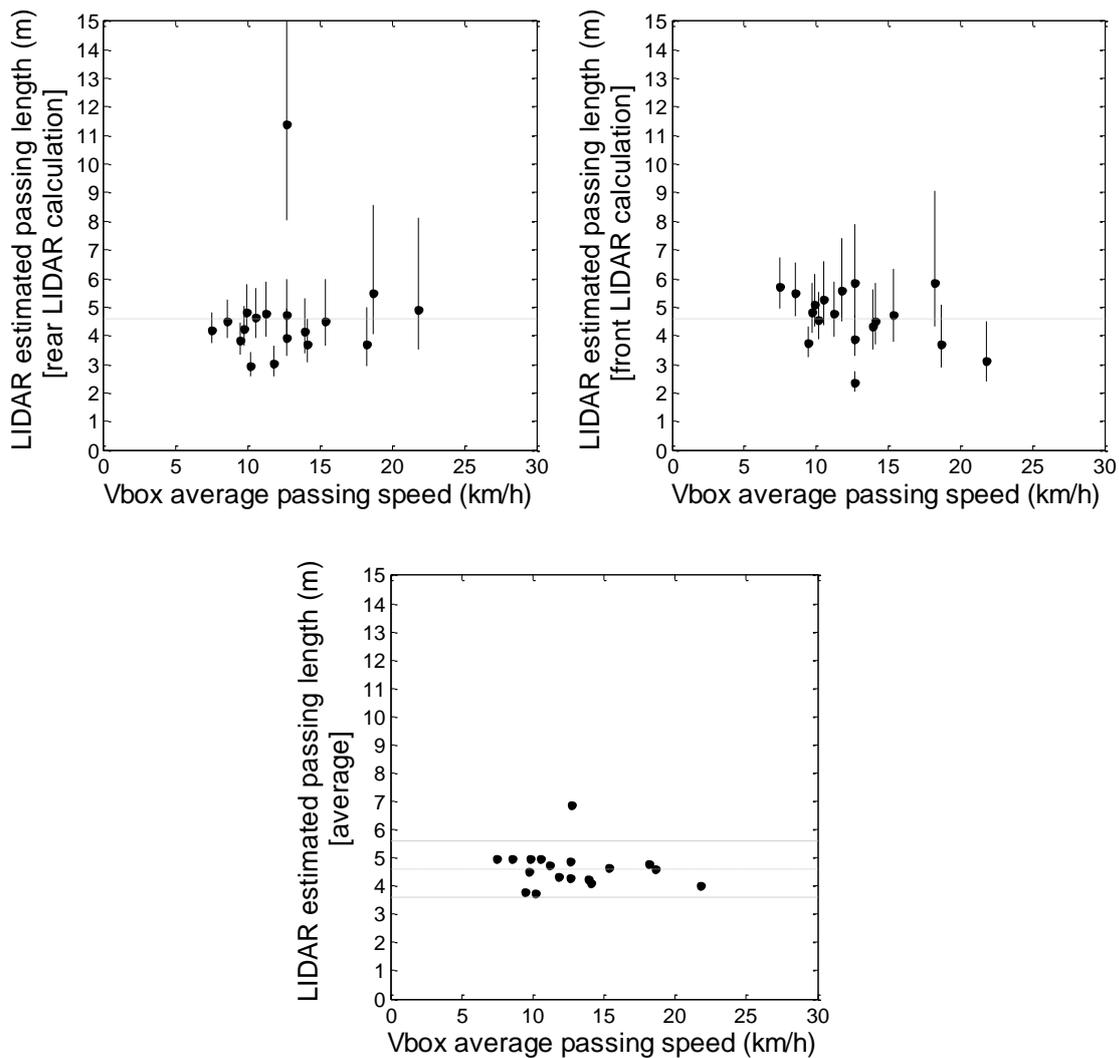
Discussion

This study has demonstrated an inexpensive method for measuring separation distances between vehicles in real traffic flows using on-board LIDAR modules. In the configuration that has been shown, the LIDAR modules were able to achieve successful readings from a vehicle located behind, to the side, and ahead during an overtaking manoeuvre. Methods for using the pair of side mounted LIDAR modules to calculate the speed and length of a passing vehicle were also demonstrated.

A Vbox dual antenna GPS system was used to validate the data readings from the LIDAR modules. A considerable proportion of the readings requested of the rear LIDAR modules were invalid compared to the front LIDAR modules but this was attributed to a greater number of requests at long range and the misalignment of the rear left module. The mean error between the valid front/rear LIDAR readings and the Vbox longitudinal range was found to be -0.4 meters. Calculation of the 90th percentile spread showed that the majority of LIDAR readings were within ± 0.65 metres of this mean.

Some of the error to the Vbox data is likely to have been caused by the shifting alignment of each LIDAR laser beam during driving. For example, the LIDAR may point at the front bumper of the vehicle behind while travelling on a flat road but if the following vehicle travels over a dip the bumper will lower and the LIDAR will strike further up the bonnet and return a longer reading.

Despite these errors, the accuracy of the LIDAR module is comparable to that of ultrasonic and video sensors used in past studies of separation distance. Additionally, the LIDAR module has a maximum range (50 meters) that is considerably further than ultrasonic or video and returns data that requires relatively little processing to utilise.

Calculations using data from the side mounted LIDAR modules predicted passing speeds that were within ± 2 km/h of the Vbox recorded average passing speed for all but one of the 18 overtaking manoeuvre test runs. While it is acknowledged that a sample size of 18 is small (and thus may not enable a complete understanding), this level of accuracy is encouraging and would be considered acceptable for many potential applications. If an application required greater accuracy then the cycle time could be decreased.

Further calculations using data from the side mounted LIDAR modules predicted the length of the passing vehicle. In all but one of the test runs, the predicted length was within ± 1 metre of the manufacturer specified length. While again acknowledging the small sample size, it is suggested that this accuracy would be sufficient to enable class of passing vehicle to be differentiated (e.g. motorcycle, car, or truck).

The findings presented here highlight the potential for the use of inexpensive LIDAR modules during studies of vehicle separation distance. The accurate measurement of longitudinal range, passing speed, and length of passing object have all been demonstrated.

However, some limitations and areas of caution were also identified during the testing process. Spurious readings were a fairly common occurrence and a filtering process was implemented in order to remove them. Despite this, some spurious readings remained (e.g. point E in Figure 2) and further, or more advanced, filtering may be required.

Highly reflective and oblique surfaces were observed to increase the chances of inaccurate readings. This was presumably the result of the LIDAR laser beam bouncing off several surfaces and returning an artificially long distance measurement.

Pointing the LIDAR module directly towards an intense light source, such as a vehicle headlight, was observed to increase the chances of a zero reading. This is unlikely to cause a problem during studies in real traffic flows as the dynamic nature of driving means the LIDAR will rarely be pointed directly into the headlights of a vehicle (and then only for a short time), but may pose an issue in other applications.

Finally, the misalignment of the LIDAR modules during installation (as was experienced in this study) can result in missed or inaccurate readings, especially at longer distances. The dynamic misalignment of LIDAR modules when travelling around bends or over uneven surfaces can also result in errors. This effect is unlikely to be overcome completely so restricting data collection to periods of straight line driving on flat roads is recommended. Utilising multiple LIDAR modules to monitor different sectors and act as a redundancy may also improve performance.

Acknowledgements

References

Garner, G. R., & Deen, R. C. (1972). *Elements of median design in relation to accident occurrence* (Research Report 348). Washington DC: Highway Research Board.

Gross, F., & Jovanis, P. P. (2007). Estimation of the safety effectiveness of lane and shoulder width: Case-control approach. *Journal of transportation engineering*, *133(6)*, 362-369.

Guthrie, N., Davies, D. G., & Gardner, G. (2001). *Cyclists' assessments of road and traffic conditions: the development of a cyclability index* (TRL Report 490). Crowthorne: Transport Research Laboratory.

Haworth, N., & Schramm, A. (2014). *The safety of bicycles being overtaken by cars: What do we know and what do we need to know?*. 2014 Road Safety Research, Policing & Education Conference, Melbourne, Australia, 12-14 November 2014.

Heesch, K. C., Sahlqvist, S., & Garrard, J. (2011). Cyclists' experiences of harassment from motorists: Findings from a survey of cyclists in Queensland, Australia. *Preventive medicine*, *53(6)*, 417-420.

Parkin, J., Wardman, M., & Page, M. (2007). Models of perceived cycling risk and route acceptability. *Accident Analysis & Prevention*, *39(2)*, 364-371.

Parkin, J., & Meyers, C. (2010). The effect of cycle lanes on the proximity between motor traffic and cycle traffic. *Accident Analysis & Prevention*, *42(1)*, 159-165.

Ponte, G., Szpak, Z.L., Woolley, J.E., & Searson, D.J. (2014). *Using specialised cyclist detection software to count cyclists and determine cyclist travel speed from video*, Australasian Road Safety Research, Policing and Education Conference, Melbourne, Victoria, 12-14 November 2014.

Pulsed Light 3D (2015). *Pulsed Light*. Retrieved June 24, 2015, from http://pulsedlight3d.com/.

Racelogic (2015). *VBOX Australia*. Retrieved June 24, 2015, from http://www.vboxaustralia.com.au/.

Stone, M., & Broughton, J. (2003). Getting off your bike: cycling accidents in Great Britain in 1990–1999. *Accident Analysis & Prevention*, *35(4)*, 549-556.

Sun, Y., & Ioannou, P. A. (1995). *A Handbook for Inter-Vehicle Spacing in Vehicle Following* (No. UCB-ITS-PRR-95-1). Berkeley: Institute of Transportation Studies.

Walker, I., Garrard, I., & Jowitt, F. (2014). The influence of a bicycle commuter's appearance on drivers' overtaking proximities: an on-road test of bicyclist stereotypes, high-visibility clothing and safety aids in the United Kingdom. *Accident Analysis & Prevention*, *64*, 69-77.