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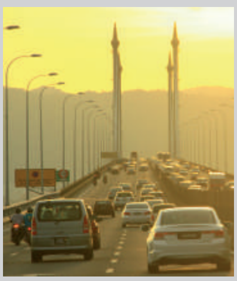
Research Report

Development of Variable Speed Limit (VSL) System on Adverse Weather Condition in Malaysian Expressway



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Abstract

A Variable Speed Limit (VSL) is a speed limit which is set dynamically, usually by digital variable message signs, so that the maximum recommended speed changes according to road conditions. There are few control strategies used for adjusting recommended speed limit, different country and different VSL product use different technique to provide recommended speed limit to road user. Thus, the aim of the research is to test the feasibility of VSL towards rain condition along Malaysian expressway.

The study finds that adopted calculation from Federal Highway Administration, US Department of Transportation is feasible to use for Malaysian weather especially rain. Theoretically, the calculation is the best option as guidance to Malaysian road user as it requires all parameter that suitable with Malaysian weather and road condition. The output of this research is a VSL product that able to give real time recommendation on optimum speed limit during rain condition. The product also gives option for user to query data based on specific date and option to download daily data to comma separated value or CSV format.

1. Introduction

Speed has a direct relation to road safety. Speed has been identified as a key risk factor in road traffic injuries, influencing both the risk of a road crash as well as the severity of the injuries that result from crashes. The relationship between speed and injury severity is particularly critical for vulnerable road users such as pedestrians and cyclists. For example, pedestrians have been shown to have a 90% chance of survival when struck by a car travelling at 30 km/h or below, but less than 50% chance of surviving an impact at 45 km/h. Pedestrians have almost no chance of surviving an impact at 80 km/h.

The speed limit is one of many causes of a road accident. In Malaysia, highway speed limit is 110 km/h, but in certain areas, it will set to lower limit (80 – 90 km/h), while 60 km/h is applied 1 km before the toll plaza. These speed limits applied to all condition of traffic, road, and weather.

In 2013, speeding was a contributing factor in 74 fatal crashes, 305 serious injury crashes and 988 minor injury crashes. These crashes resulted in 83 deaths, 421 serious injuries and 1,442 minor injuries (Ministry of Transport, New Zealand, 2014). While in Malaysia, if we look into driver error, speeding was a contributing factor in 70 fatal crashes, 73 serious injuries and 110 minor injuries for the year 2013 (PDRM).

The problem with the existing speed limit is there is no guidance on safe speed to travel in various weather conditions. Existing speed limit post the limit for general or good weather condition. This limit is not suitable for adverse weather condition. Driving too fast in adverse weather condition like rain, windy, and foggy can create a chance for a road accident. As an example, the speed limit for the highway in Malaysia is 110 km/h. The posted speed limit is good for normal weather condition, but for adverse weather condition, the posted speed limit should be reduced to the certain extent that matches with current weather condition.

1.1 Accident Trend in Malaysia

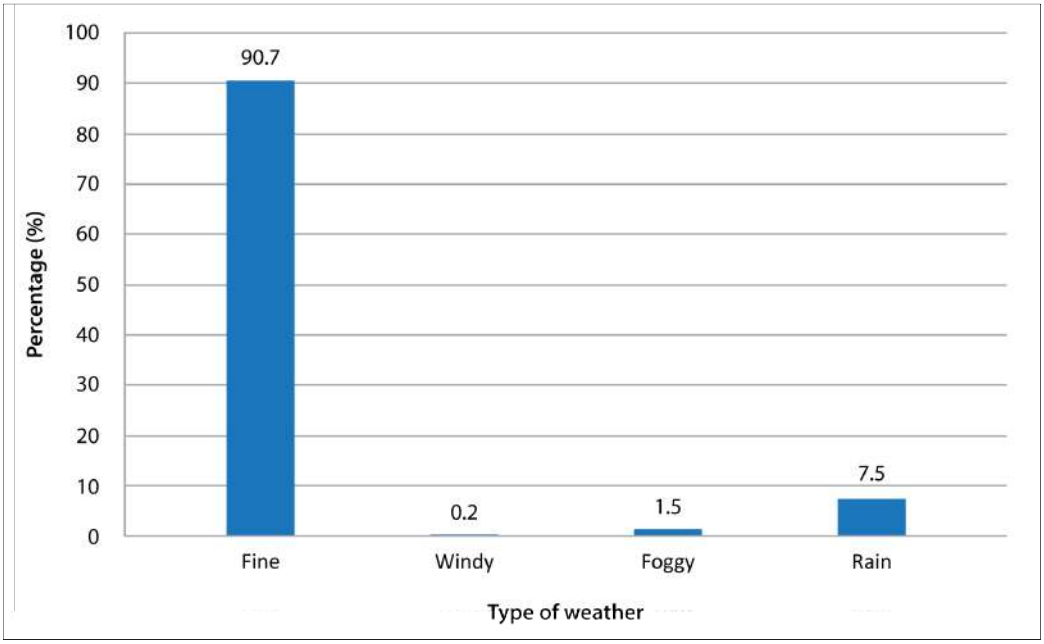

Figure 1 Percentage for average of fatal cases between the year 2008 – 2012

Figure 1 shows that various type of weather affected total of fatal road accident. Total percentage for the year 2008 until 2012 for fine is 90.7%, windy is 0.2%, foggy is 1.5%, and rain is 7.5%.

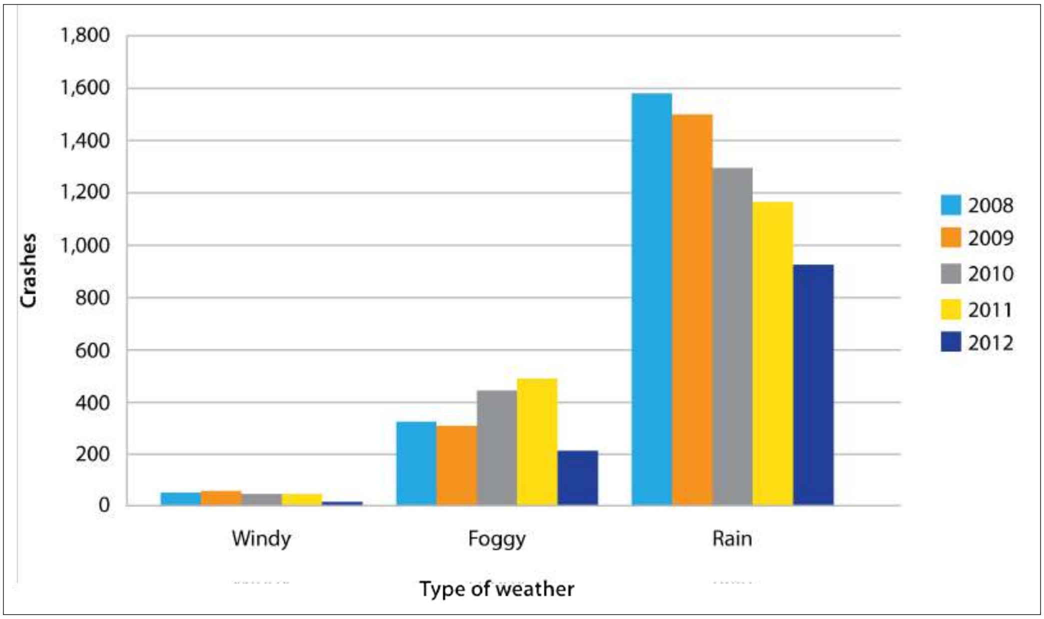

Figure 2 Total of crash VS weather by year in Malaysia

As shown in Figure 2, various type of weather affected total of road accident. Total percentage for the whole year for fine is 92.15%, windy is 0.20%, foggy is 1.65%, and rain is 6%.

In the US, between 2000 and 2009 there were a total of 371,104 fatal crashes. 46,811 or 12.6% of these crashes occurred on wet pavement (Fatality Analysis Reporting System website).

Weather impact on driver acts through visibility impairments, precipitation, high winds, and temperature extremes to affect driver capabilities, vehicle performance (i.e., traction, stability and manoeuvrability), pavement friction, and roadway infrastructure. These impacts can increase crash risk and severity (Paul, 2008).

1.2 Aim and Objectives of the Study

This study aims to produce a product that able to process and generate recommended speed limit for adverse weather condition.

In order to achieve the aim, several objectives have defined:

i. To determine recommended speed limit for various situation of weather by developing or adapt formula, calculation, model, or logic;
ii. To develop VSL product that suitable for Malaysian weather.

1.3 Scope and Limitation of the Study

This study focuses on rain for pilot and theoretical testing. The formula used was adapted from Federal Highway Administration, U.S. Department of Transportation. However, the formula was mainly used for snow condition in the US. Due to that, another formula to get visibility was used. The result from the formula then will pass to core formula to generate recommended speed limit. Other types of adverse weather condition like windy and foggy will not be tested in this study.

2. Literature Review

The focus of the literature review is the model, formula and calculation on recommending speed limit for adverse weather condition. Various type of VSL product use different approach to determine recommended speed limit. Some of the factors for the approach are weather, road surface condition, and regulation on the speed limit.

2.1 Weather Impact towards Safety

Table 1 Weather impacts on roads, traffic and operational decisions (FHWA, 2015)

Road weather variables	Roadway impacts	Traffic flow impacts	Operational impacts
Air temperature and humidity	N/A	N/A	- Road treatment strategy (e.g., snow and ice control) - Construction planning (e.g., paving and striping)
Wind speed	- Visibility distance (due to blowing snow, dust) - Lane obstruction (due to wind-blown snow, debris)	- Traffic speed - Travel time delay - Accident risk	- Vehicle performance (e.g., stability) - Access control (e.g., restrict vehicle type, close road) - Evacuation decision support
Precipitation (type, rate, start/end times)	- Visibility distance - Pavement friction - Lane obstruction	- Roadway capacity - Traffic speed	- Vehicle performance (e.g., traction) - Driver capabilities/ behaviour

		- Travel time delay - Accident risk	- Road treatment strategy - Traffic signal timing - Speed limit control - Evacuation decision support - Institutional coordination
Fog	- Visibility distance	- Traffic speed - Speed variance - Travel time delay - Accident risk	- Driver capabilities/ behaviour - Road treatment strategy - Access control - Speed limit control
Pavement temperature	- Infrastructure damage	N/A	- Road treatment strategy
Pavement condition	- Pavement friction - Infrastructure damage	- Roadway capacity - Traffic speed - Travel time delay - Accident risk	- Vehicle performance - Driver capabilities/ behaviour (e.g., route choice) - Road treatment strategy - Traffic signal timing - Speed limit control
Water level	- Lane submersion	- Traffic speed - Travel time delay - Accident risk	- Access control - Evacuation decision support - Institutional coordination

Table 1 shown that precipitation has the most impact towards roadway, traffic, and operational (Federal Highway Administration, US Department of Transportation). In Malaysia, this also supported by crash data, which rain is the highest among other adverse weather conditions. Other than all the road weather variables shown in Table

1, crosswind also one of the factors that can contribute to road crash. Certain highway in Malaysia have this effect like PLUS (KM212 and KM196).

Another factor that not included in Table 1 is excessive sun glare. Studies have shown that permanent damage to the eyes can result from prolonged exposure to the sun without adequate protection. This will make vision obstruction when driver exposes to direct excessive sun glare.

It is widely accepted that weather has an influence on road safety since the weather conditions partly determine the road conditions and driver's behaviour (SWOV, 2012).

Weather is an environmental factor that affects collision and casualty rates. Various weather conditions can be safety threats, such as reduced road friction, which leads to more slippery road, limited visibility and other adversities that can make vehicle handling very difficult and dangerous. Such situations are more frequent during adverse weather conditions, such as heavy rainfalls (Dimitrios, 2013).

Weather conditions can influence traffic as well. Empirical findings suggest that traffic volume is usually lower during inclement weather than during "normal" conditions. Also, the presence or expectation (based on weather forecasts) of unfavourable weather conditions may affect the mode choice and driver behaviour, something which can consequently affect road safety (Dimitrios, 2013).

The majority of papers in the literature examine the effect of adverse weather on the frequency and the severity of crashes in various types of facilities (Khattak et al., 1998; Knapp et al., 2000). Qiu and Nixon (2008) presented a systematic review and meta-analysis on the effect of adverse weather on road crashes. The major finding of that work was that most precipitation events were associated with a considerable increase in both crashes and crash rates, with snow having a greater effect than rain.

The crash analysis revealed that most weather-related crashes happen in presence of rain and wet pavement (Lynette, 2003).

Fog and smoke contribute to head-on and rear-end collision because of limited visibility (Mohamed et al., 2010).

2.2 Speed Limit along Malaysian Expressway

To avoid road accident, Malaysian authority has declared the speed limit to all type roadways, which is fixed/static speed limit. The weakness of fixed/static speed limit cannot adjust immediately to respond to changing traffic, road, and most importantly weather condition.

Malaysia's weather can be described as being hot and humid throughout the year. The average rainfall is 250 centimetres (98 inches) a year and the average temperature is 27°C (80.6°F). These varieties of weather can affect the road accident in Malaysia.

This is related to speed limit that permanently decides to all type of weather. When the weather has changed, other factors like sight distance, the efficiency of car safety equipment, and driver awareness also change. When not all these factors being considered, it will make road accident easily to happen.

Therefore, in such situation, implementation of the variable speed limit system in Malaysian roadway is crucial in the context of road safety. By doing so, road accident rate can be reducing.

2.3 Variable Speed Limit (VSL)

Variable Speed Limit (VSL) is a mainline traffic control technique that has been increasingly used for improving traffic safety on roadways (Robinson, 2000; Lee et al., 2006; Abdel-Aty et al., 2006; Allaby et al., 2007; Hellinga & Mandelzys, 2011; Islam et al., 2013; Lee et al., 2013; Hadiuzzaman & Qiu, 2013; Li et al., 2014; AlKaisy et al., 2012; Ali, 2008; Bertini et al., 2006; Buddemeyer et al., 2010; Han et al., 2009; Jonkers et al., 2008; Rama & Schirokoff, 2004; Hassan et al., 2011; FHWA, 2012). The central idea of VSL is to intervene proactively by adjusting speed limits on roadside variable speed limit signs.

The use of VSL during inclement weather can improve safety by decreasing the risks associated with traveling at speeds that are higher than appropriate for the conditions.

When traveling on roadways drivers need to see roadways head to make emergency responses to dangerous traffic situations. During severe weathers, the poor visibility and road surface condition generally results in a shorter sight distance and a longer stopping distance. After a traffic collision occurs, approaching vehicles from upstream sections may not observe the slow traffic induced by the collision promptly. As a result, a secondary collision is highly likely to occur after the occurrence of the initial collision. Even though some drivers tend to drive slowly and keep a longer car following distance, a secondary collision could still occur in some extreme situations.

2.3.1 Available VSL System in Market

Table 2 VSL system available in market (Al-Kaisy et al., 2012)

Location	Measures	Roadway type
Tasman Highway, Australia	Road, traffic, and weather condition	Highway
Michigan	Weather, work zone, congestion	Work zone
Finland	Road and weather condition	Highway
Alabama	Visibility	Interstate

2.3.2 VSL Control Strategy

Table 3 Weather-related VSL control strategies available in market (Al-Kaisy et al., 2012) and proposed system in Malaysia

State/Country	Parameter	VSL control strategy
Alabama, US	Fog	Change speed limit in increments of 10 mph within range 35–65 mph in five visibility distance levels
Delaware, US	Precipitation, wind, reduced visibility	Reduce speed limit by 5–20 mph in inclement weathers

South Carolina, US	Precipitation	Reduce speed limit to 45 mph
Washington, US	Rain, snow, fog	Speed limit varies between 35 and 65 mph in 10 mph increments in four types of weather conditions.
Wyoming, US	Visibility, surface condition, snow, wind	Speed limit varies between 35 and 75 mph due to visibility and surface conditions
Arizona, US	Road surface, visibility, wind	Incorporate fuzzy logic to identify appropriate speed limits for different environmental conditions $$x = \frac{(-3.67 + \sqrt{13.47 + \frac{0.12}{\mu \pm G} * (S)}\,)}{\frac{0.06}{\mu \pm G}}$$ $x = speed\ limit$ $\mu = coefficient\ of\ road\ adhesion$ $G = roadway\ grade$ $S = sight\ distance$
Tennessee, US	Fog	Speed limit varies between 35 and 65 mph due to visibility conditions
Utah, US	Fog	Speed limit varies between 25 and 65 mph due to visibility conditions
Australia	Inclement weather	The speed limits were set to 60, 80 or 100 km/h based on observations made via CCTV imagery
Finland	Wind, rain, road surface condition	Set 120 km/h for good conditions; 100 km/h for moderate conditions; 80 km/h for poor conditions
Netherlands	Rain	Reduce speed limit to 50 mph according to water on road surface and rain intensity
Netherlands	Visibility, incident	Reduce speed limit to 80 km/h and 60 km/h according to visibility distance; reduce speed limit to 50 km/h if incident was detected
Saudi Arabia	Fog	Reduce speed limit to 40 km/h during foggy conditions
Swedish	Precipitation, road surface condition	Reduce speed limit to 110 km/h if the friction is 0.4; reduce speed limit to 100 km/h if the friction is 0.3;

		reduce speed limit to 80 km/h if the friction is 0.2; reduce speed limit to 60 km/h if the friction is 0.1
Malaysia	Weather condition	Logic or rule-based model to calculate speed limit.

Previously, various VSL control strategies have been used in practice to improve traffic safety during inclement weathers (see a summary in Table 3). The common control logic in those strategies is to use a pre-set speed reduction if the current condition is less than ideal. However, only some fixed values of speed limits are recommended for several levels of weather conditions. The speed limits are usually determined according to practical experiences.

Implementation of VSL can lead to many benefits. The system can recommend speed limit without involving operator existence in the scene area. The system just needs to enter preliminary information for calculation purpose. Other than that, just leave it to sensor and processing unit to do the whole process. In another word, the whole system has the ability to respond to various weather conditions and recommend suitable speed limit.

Reduce accident rate is very important benefit from the implementation of VSL. This can be done by giving recommended speed limit to the driver to make sure their travel and journey success and no accident. This can lead to road safety improvement and smooth traffic flow.

In terms of road safety, VSL leads to several positive impacts. VSL can improve safety by helping to reduce primary and secondary crashes during adverse weather conditions and congestion. By implementing more uniform driver behaviour and uniform speeds, drivers are less likely to drive erratically, reducing the likelihood of crashes. Furthermore, the reduced speeds help reduce the severity of incidents that might occur.

VSL can help delay the onset of congestion. With more uniform speeds and decrease headways, traffic flows more smoothly and efficiently, which can improve trip travel time reliability. Environmental benefits with variable speed limits can include decrease emissions, decreased noise, and decreased fuel consumption.

3. Methodology

This research involves the development of VSL framework to recommend the speed limit filtered by weather condition. The framework consists of four parts, which are pre-processing, data collection module, a processing module, and dissemination of information module. Inside pre-processing, data collection for fixed value will be done. Inside data collection module, the process is live data collection. While for processing part, the service installed inside processing unit will calculate, recommend speed filtered by data received from the input. Inside dissemination of information module, it will show the recommended speed limit to VMS.

In order to ensure the recommended speed limit is suitable and relevant to Malaysian roadway, a baseline data on vehicle speed during adverse and good weather condition will be conducted. This will get information on the speed of the vehicle during adverse weather condition, and the different of vehicle speed between adverse and good weather condition. Then the data will be analysed to know the relevancy of the recommended speed limit.

3.1 VSL Framework

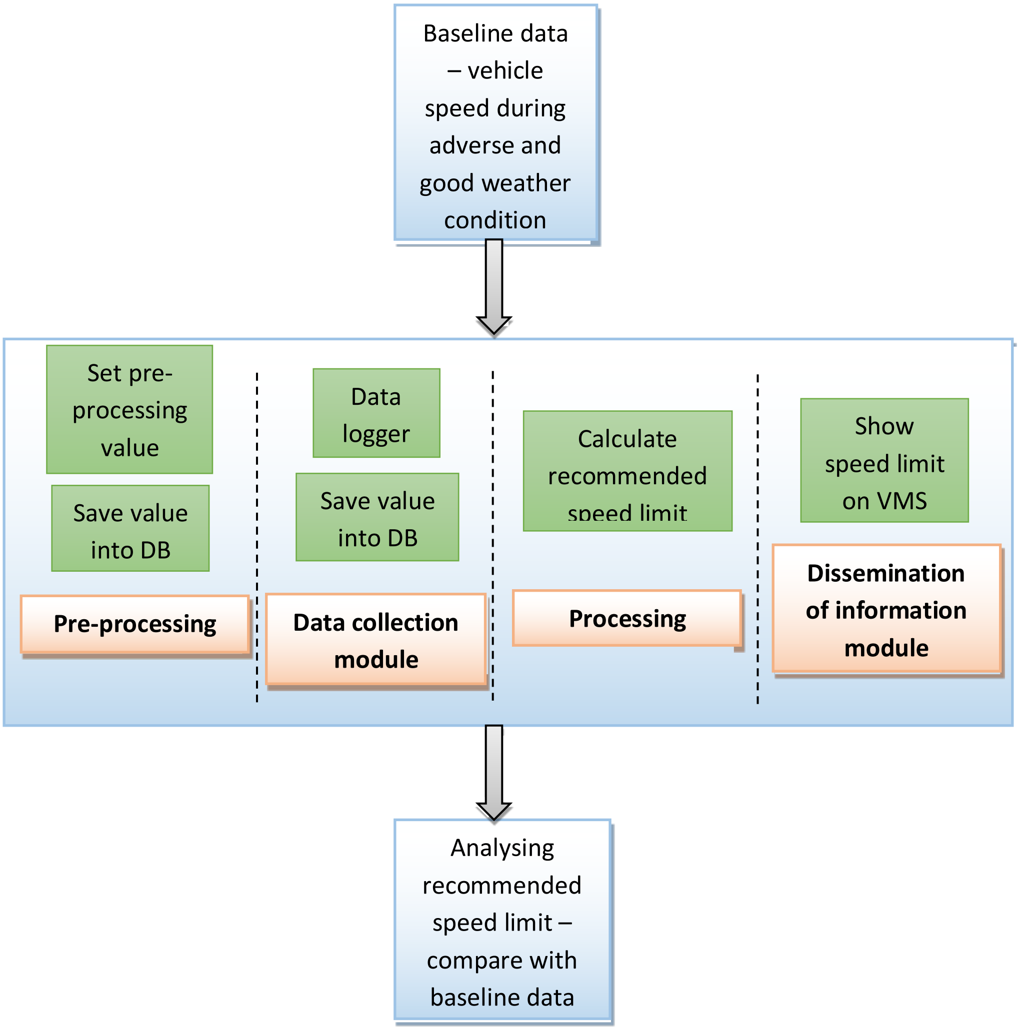

Figure 3 Proposed VSL framework

Baseline Data

Get vehicle speed during several adverse weather conditions. The data will use later when VSL finished.

Pre-Processing

In this process, the user needs to do some field work and calculation to set the needed value. The values are coefficient of adhesion of the road, and roadway grade. Those values can be set by using skid resistance and laser distance equipment. All the value need for calculation in processing part. Then, the values will be key in inside the application in processing unit. These values will be saved inside the database in processing unit. The values are needed only one time before VSL install and start.

Data Collection Module

Input part can be considered an important part of the process. This will involve weather station device. It will measure rainfall, sight distance, and wind velocity. The device frequency to update data is every 1 minute. Then, all the data will be sent to processing unit for next process. Each data received also will be stored in the database in processing unit.

Processing Module

This is the crucial part when data manipulation will be done. The processing unit will be installed with application to process the data received from the input. The application is developing with NET base-framework. It will run as windows-application and automatic launch on OS start.

Dissemination of Information Module

After all, the data being processed, the processing unit will send recommended speed limit to VMS.

Analysing Recommended Speed Limit

After VSL is done recommending speed limit, all the saved speed data will be compared to baseline data. This to ensure recommended speed limit by VSL can help to increase road safety and as proof that driver not using suitable speed limit during adverse weather condition.

4. Results and Discussions

This section discusses the results and findings of the study. This section is divided into two subsections; VSL product, and formula and control strategy used for speed limit recommendation.

4.1 Speed Characteristics Analysis

Speed data was collected on SILK Expressway (E18) on 14th July 2015 when it was raining. Traffic for two directions were collected; traffic direction to Putrajaya and Semenyih.

Table 4 Speed analysis

	Average speed		85th percentile speed	
	Putrajaya	**Semenyih**	**Putrajaya**	**Semenyih**
Car	94	84	103	92
Lorry	71	64	83	76
Motorcycle	75	71	93	85

The average speed for cars was 94 kph and 84 kph for traffic direction to Putrajaya and Semenyih respectively. This indicated that cars travel the fastest among the observed vehicle. Meanwhile, the average speed of motorcycle was 75 kph and 71 kph for traffic direction to Putrajaya and Semenyih respectively. Motorcycle speed was recorded to be lower that the speed of the cars. Lastly, lorries were the slowest among the vehicle with the average speed of 71 kph and 64 kph for the traffic direction to Putrajaya and Semenyih respectively.

The 85th percentile speed is one of the criteria to use to set the speed limit on the roads. The 85th percentile speed is also known as the operating speed. The data indicated that only lorries heading towards Semenyih has the operating speed 76kph which is below the speed limit of 80kph. Other than that, it was observed that the vehicle was travelling above the speed limit. Even though it was raining, most road users were observed driving more that the speed limit.

Independent sample t-tests was carried out to compare the mean between the speed on different direction. Generally, there was a significant difference between the travel speed to Putrajaya and Semenyih ($p < 0.05$). However, there was no significant difference in speed between motorcycle travelling to Putrajaya and Semenyih ($p = 0.167$).

The t-test was carried out to compare the mean of speed between different vehicles. Generally, there were significant different between the speed of cars and motorcycles, cars and lorries and motorcycles and lorries ($p < 0.05$). However, there was no significant different in speed between motorcycles and lorries that was travelling in the direction to Putrajaya ($p > 0.05$).

4.2 Skid Resistance

Figure 4 Skid resistance test

Skid resistance test were conducted on dry and wet pavement on tire track. The three readings at three point were 60, 58 and 58. These value then will converted to coefficient of road adhesion that then will be used in generating recommended speed.

4.3 VSL Product

Figure 5 The VSL & 3D drawing

Figure 5 shows the VSL product when completely assembled. There are seven (7) components involved in the assembly process. They are:

1. RG-100 Tipping Bucket
2. W-100 Anemometer
3. SDB-100 Lite Smart Logger
4. 2 Meter Mast Tripod
5. Rain-proof Enclosure
6. Battery & Charge Controller
7. Software

RG-100 Tipping Bucket is a rain gauge tipping bucket that able to collect and measure the amount of rain that falls. W-100 Anemometer is an instrument for measuring the speed of wind. This instrument comes with wind direction sensor. SDB-100 Lite Smart Logger is a powerful logger that will integrate with all sensors. This data logger then will provide smooth data processing. 2 Meter Mast Tripod will hold all equipment together. This tripod is made of stainless steel. Rain-proof Enclosure is a plastic enclosure that will cover the processing unit from rain. Battery & Charge Controller will receive power from the solar panel and then send power supply to all sensors and to the power up processing unit.

4.3.1 Processing Unit

Figure 6 Processing unit

The processing unit/board used in this product is Raspberry Pi. This board is a small sized computer that able to simulate full-scale computer capability and powered by a battery that can be charged using solar technology. This processing unit will retrieve real-time data from the rain gauge, anemometer, and wind direction that then will do a calculation to provide recommended speed limit.

4.3.2 Real-Time Data

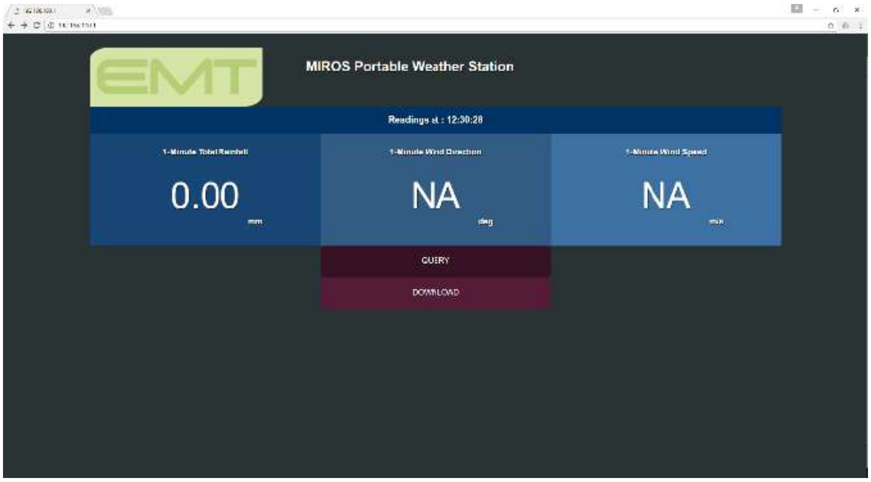

Figure 7 Web interface – Dashboard

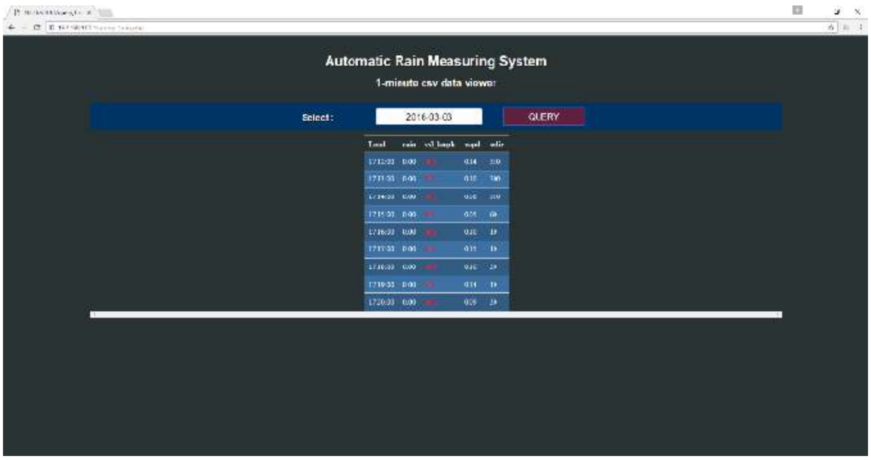

Figure 8 Web interface – Data viewer

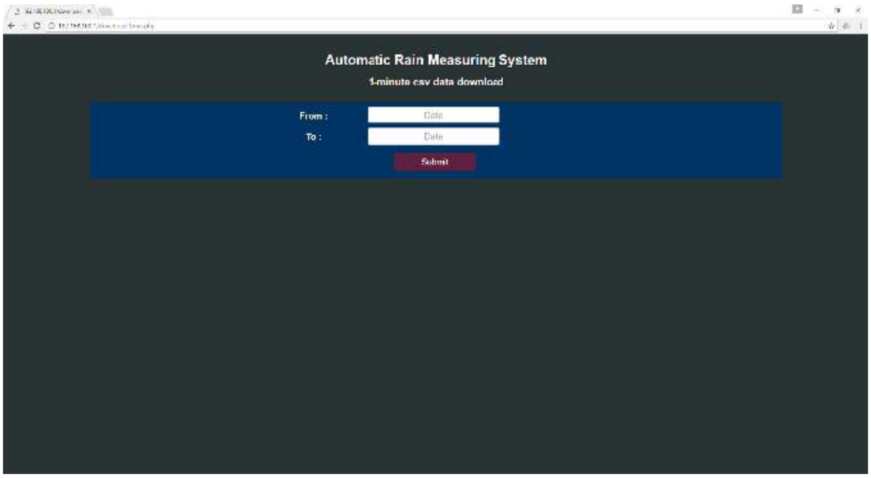

Figure 9 Web interface – Data download

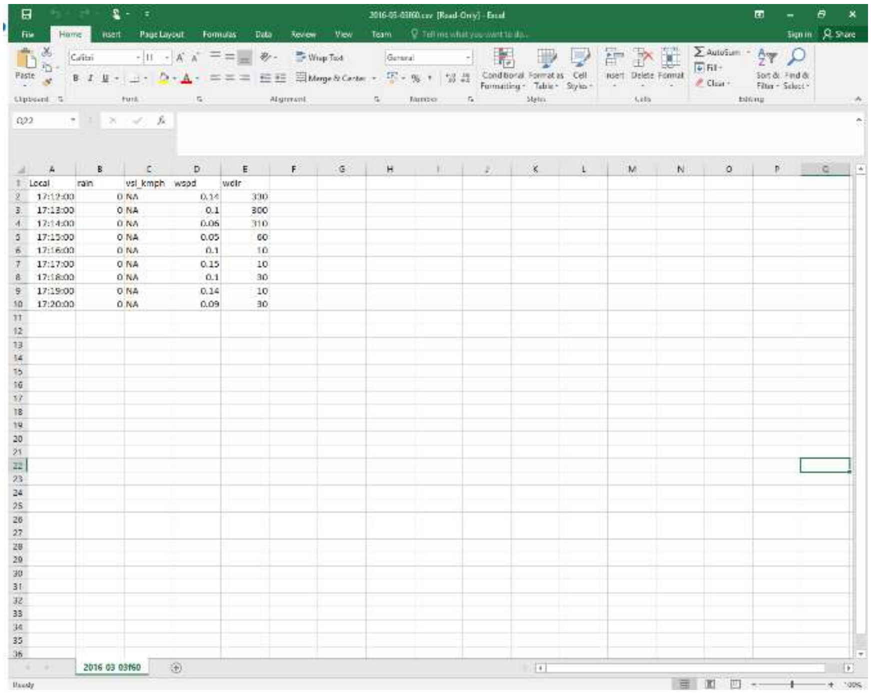

Figure 10 Web interface – Downloaded Excel

The processing unit also can be accessed via local communication. Any computer can connect to the unit as long as it connected to the same network. The connected computer then can access web-based system of the processing unit to get data from the sensor.

The web-based system consists of three main modules; dashboard or real-time data (Figure 5), data viewer (Figure 6), and data download (Figure 7). Dashboard or real-time data contain current information of connected sensors, which are rain (mm), wind speed (m/s), and wind direction (degree). The value on dashboard updated every 1 minute. While data viewer is the platform where the user can view data for specific date. The user has to select a specific date and then click on query button to view data of chosen date. All data including recommended speed limit then will appear on the panel as shown in Figure 6. To give more option for the researcher to manipulate retrieved data from sensors, the system provides platform for data downloading. This platform allows user to select a date range, and then click on submit button to start query and download. As shown in Figure 7, downloaded data will come in CSV (Comma Separated Values) format, which can be open using any text/spreadsheet reader software.

4.4 Formula and Control Strategy for VSL

$$x = \frac{(-3.67 + \sqrt{13.47 + \frac{0.12}{\mu \pm G} * (S)}\,)}{\frac{0.06}{\mu \pm G}}$$

$$x = speed\ limit$$
$$\mu = coefficient\ of\ road\ adhesion$$
$$G = roadway\ grade$$
$$S = sight\ distance$$

Figure 11 Formula used for VSL (Federal Highway Administration, US Department of Transportation)

Figure 11 shows the formula chosen to be implemented in VSL product that developed from this study. This formula is the best that chose among others as shown in Table 5. The formula can be implemented as it requires data that available along Malaysian expressway. The value for μ and *G* has to measure before VSL start running. This will be preliminary data that have to set earlier. The value for *S* then will automatically generate from the formula of (S = 4550/rain density * 0.68). The value for rain density will get from live data from rain gauge tipping bucket.

Table 5 Example of calculation based on rain density taken from Malaysian Meteorological Department

Speed limit (km/h)	Coefficient of road adhesion	Roadway grade	Sight distance (feet)	Rain density (mm)
77.16	0.6	0	290.92	23
361.39	0.6	0	3345.59	2

As shown in Table 5 to simulate the formula, daily rainfall for Petaling Jaya on 28th November 2016 is 23.0 mm. While assuming current road gradient is 0%, and road adhesion is 0.6 (if the actual values are not known, one can assume a value of road adhesion of 0.6). The other example that can be used to simulate the formula is when daily rainfall for Batu Pahat on 28th November 2016 is 2.0 mm.

The system then should cap recommended speed limit to follow postage speed limit in a particular area. As an example, on Batu Pahat North-South Highway KM 90 postage speed limit is 110 km/h. Then VSL should cap the recommended speed limit up to 110 km/h.

5. Conclusion and Recommendations

This study has three main objectives. The first objective is to provide recommended speed limit for the adverse weather condition in Malaysian expressway. There are many ways to provide recommended speed limit, and the variable speed limit system is one option for it. VSL is the best as it can calculate recommended speed limit automatically based on rainfall and any other factor if needed. VSL also opted for its portability and a stand-alone processing unit. This makes arrangement and placement of VSL much easier.

The second objective is to determine recommending speed limit for the various situation of weather by developing model or logic for speed limit calculation. However, due to time constraint and the various option of existing model or logic in the market, formula from Federal Highway Administration, US Department of Transportation was chosen. This formula is the best among the other control strategy as it can be used for the weather condition in Malaysia.

The last objective is to develop VLS product that suitable for Malaysian weather. The product successfully develops but yet to test on actual site and Malaysian environment. Theoretically, the combination of sensors, a processing unit, and formula to calculate recommended speed limit is usable in for rain condition.

As a consequence of this study, the following recommendations are proposed:

i. Guideline on VSL placement should be developed;
ii. Encourage road authority to provide recommended speed limit on adverse weather condition. A recommendation of both lowest and highest speed limit will be better.

Recommendations for future study:

- This project adopted the formula from U.S. Department of Transportation. Hence, a further study on evaluation of recommended speed limit is crucial.
- A further study on criteria/guideline of placement on VSL in Malaysian road.
- A further study on speed behaviour during adverse weather condition.

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Research Report

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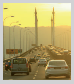

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