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MODELLING THE RHEOLOGICAL PROPERTIES OF BITUMINOUS BINDERS USING A MECHANICAL MODEL

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ABSTRACT

Modelling is a very useful way to fit or describe the linear viscoelastic (LVE) properties of bituminous binders, which cannot be done via laboratory work. This study investigates the applicability of LVE rheological models called the 2S2P1D (combinations of two springs, two parabolic elements and one dashpot) model on different types of bituminous binders. The rheological data of unaged and aged unmodified bitumens, bitumen-filler mastics and polymer-modified bitumens were measured using a dynamic shear rheometer (DSR) in the LVE region. It was found that this model with seven parameters fits the measurements reasonably well over a wide range of temperatures and frequencies. The correlation between measured and descriptive data was evaluated by means of the goodness-of-fit statistics method. Except for the unaged polymer-modified bitumens, the other samples show good agreement between the measured and descriptive complex modulus and phase angle data.

Keywords: *Bitumen-filler mastic, Linear viscoelastic, Modelling, Polymer modified bitumen, Unmodified bitumen*

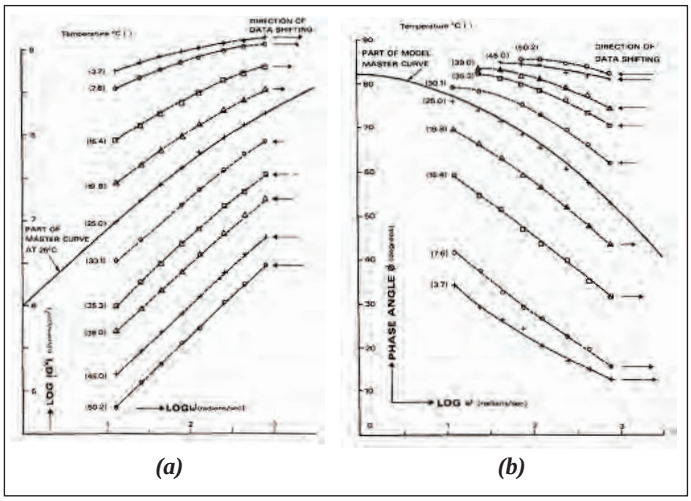
1.0 BACKGROUND

Traditionally, the behaviour of unmodified bitumen is evaluated using empirically based tests as part of penetration or viscosity graded specifications. The primary purpose of these specifications is to grade the unmodified bitumen according to its consistency and, therefore, they do not address specific distress modes or ensure good long-term field performance. With the increased use of bitumen modifications such as polymers and mastics, there is a need for fundamental binder testing, where the classical tests have proved inadequate, to describe the viscoelastic properties needed for a complete rheological evaluation of bitumens [1]. One such fundamental test is a dynamic shear rheometer (DSR), which was introduced during the Strategic Highway Research Program (SHRP) campaign. The DSR is a very useful tool to determine the elastic, viscoelastic and viscous properties of bituminous binders over a wide range of temperatures and frequencies [2]. This instrument, however, has a limitation: at high frequencies and/or low temperatures, data are exposed to testing errors from the rheometer [3-5]. Moreover, it is time-consuming, expensive and requires operation by skilled personnel if complete linear viscoelastic (LVE) properties are to be obtained.

Alternatively, the introduction of modelling is very useful to fit or describe the rheological properties of bitumen which cannot be obtained through experimental work. In general, there are several methods used to represent the rheological properties of binders: nomograph, mathematical equation and mechanical model. Historically, the development of the rheological models is dated circa 1950s when the Van der Poel's nomograph was introduced [1]. However, nomographs become obsolete with time and tended to be replaced with mathematical and mechanical models. In the mathematical equation approach, one simply has to adjusts any mathematical formulation whatsoever to the experimental main curve, with the quality adjustment being the sole criterion of choice of formulation. Meanwhile, in the mechanical element approach, use is made of the fact that the behaviour of LVE material can be represented by a combination of spring and dashpot mechanical models, resulting in a particular mathematical equation [6]. A number of studies have been conducted to develop rheological models, and all of them are generally able to satisfactorily describe the rheological properties of unmodified bitumen in the LVE region.

Normally, the dynamic shear data are presented as complex modulus $|G^*|$ and phase angle δ master curves, as shown in Figure 1 [7]. A good master curve should appear smooth and continuous. The technique of determining the master curve is based on the time-temperature superposition principle (TTSP) correspondence, which uses the equivalence between frequencies and temperatures to determine the moduli of bitumens. This principle involves the horizontal movement [8]. A standard reference temperature (T_{ref}) needs to be selected and the rheological data at all other temperatures shifted with respect to frequency until the lines merge into a single form. The amount of shifting required at each temperature to form the master curve is called the shift factor a_T. Materials whose rheological properties can be shifted by TTSP to produce a smooth, continuous master curve are termed thermo-rheologically simple materials [9].

According to Chailleux *et al.* [10], the construction of master curves only makes sense if there are no major structural rearrangements such as phase changes, and tests are conducted within the LVE response. Through the use of the master curve and shift factor relationships, it is possible to interpolate stiffness at an expanded range of frequencies and temperatures compared with those at which the data was collected. If functional forms are fitted to the shape of the master curve plot and to the shift factor relationship this interpolation becomes rapid and easy to apply in computer software. In addition, if a functional form with some thermodynamic basis is used then the resulting equations can be employed to extrapolate the data beyond the observed range of temperatures and frequencies [11].



(a) *(b)*

Figure 1: The construction of the (a) |G*| and (b) δ master curves [7]

From the literature, the 2S2P1D model was found to be a unique rheological model that is capable of fitting or describing the rheological properties of both the binder and asphalt mixture. This model was originally calibrated at the *Ecole Nationale des Travaux Publics de l'Etat* (ENTPE) laboratory using annular shear rheometer (ASR) data [12]. However, the validity of this model also needs to be assessed by other types of rheometers. Therefore, the objective of this study is to evaluate the suitability of the 2S2P1D model to describe the rheological properties of various binders from the dynamic shear rheometer (DSR) tests. The correlation between the measured and descriptive data is evaluated using the goodness-of-fit statistics method for both $|G^*|$ and δ master curves.

2.0 THE 2S2P1D MODEL

The 2S2P1D, an abbreviation of the combinations of two springs, two parabolic creep elements and one dashpot, is a unique model to fit or describe the rheological properties of binders and asphalt mixtures in the LVE region [12-14]. This model, as shown in Figure 2, is based on the generalisation of the Huet-Sayegh model (combinations of two springs and two parabolic elements in series).

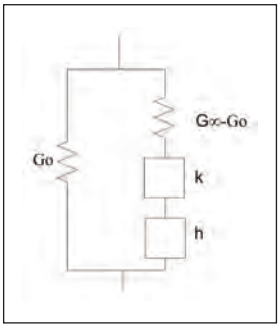


Figure 2: The 2S2P1D model [12]

According to Olard and Di Benedetto [12], a parabolic element is an analogical model with a parabolic creep function, and is shown as the following:

$$J(t) = a\left(\frac{t}{\tau}\right)^h \tag{1}$$

The complex modulus function is given by:

$$G^* = \frac{(i\omega\tau)^h}{a\Gamma(h+1)} \tag{2}$$

where $J(t)$ is the creep function, h is the exponent where $0 < h < 1$, a is a dimensionless constant, t is the loading time, τ is the characteristic time (which value varies only with temperature), i is the complex number $(i = \sqrt{-1})$ and ω is the angular frequency. Γ is a gamma function and defined as:

$$\Gamma(n) = \int_0^\infty t^{n-1} e^t \, dt \tag{3}$$

where n is the number of points. The 2S2P1D model consists of seven parameters (G_∞, G_o, α, k, h, β and τ_o) and the complex modulus equation is shown as follows:

$$G^* = G_o + \frac{G_\infty - G_o}{1 + \alpha(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}} \tag{4}$$

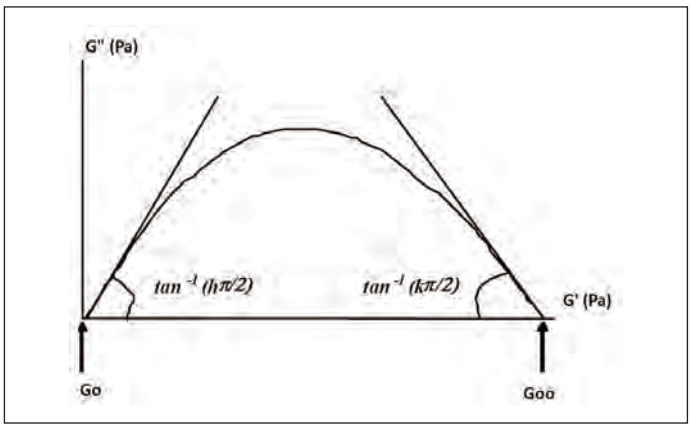
where k and h are the exponents with $0 < k < h < 1$, α is a parameter, G_o is the static modulus when $\omega \to 0$, G_∞ is the glassy modulus when $\omega \to \infty$. Meanwhile, β is a parameter and obtained from:

$$\eta = (G_\infty - G_o) \times \beta \times \tau \tag{5}$$

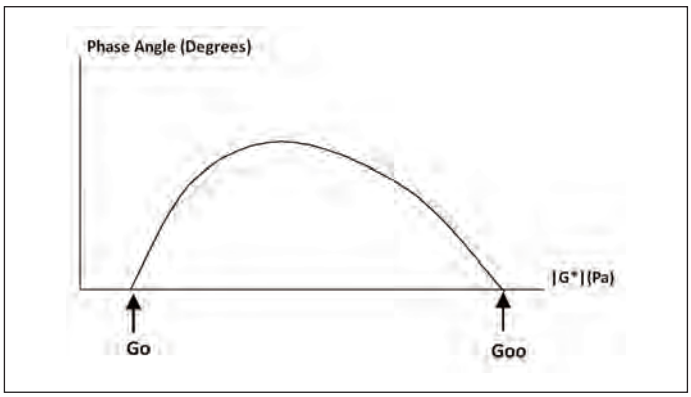
where η is the Newtonian viscosity and τ is a characteristic time that is only dependent of temperature and takes into account TTSP. The evolution of τ can be approximated by a shift factor law such as shifting the curve manually, the William, Landel and Ferry (WLF) equation and Arrhenius equation in the range of temperatures observed in the laboratory [12-14]:

$$\tau = a_T(T) \times \tau_o \tag{6}$$

where $a_T(T)$ is the shift factor at temperature T_i, and τ_o is determined at the reference temperature T_{ref}. The 2S2P1D model only needs seven parameters to determine the entire rheological properties of materials [12]. The parameters (G_o, G_∞, k, h, and β) are determined iteratively to achieve the best fit that can be obtained in the Cole-Cole diagram and Black diagram respectively (Figures 3 and 4) [15]. By definition, the Cole-Cole diagram is a graph of the loss modulus G'' as a function of the storage modulus G' and the Black diagram is a graph of $|G^*|$ versus δ [6].



(a) The Cole-Cole diagram



(b) The Black diagram

Figure 3: Graphical representation of the model's parameters in term of (a) the Cole-Cole diagram and (b) the Black diagram [15]

Meanwhile, the phase angle δ is determined using the classical equation, shown as follows:

$$\delta = \tan^{-1}\left(\frac{G''}{G'}\right) \tag{7}$$

where the symbols are as previously defined. All the parameters are adjusted to ensure that the model's curve is superposed with measurements. This process is manually.

3.0 GOODNESS-OF-FIT

Three statistical methods are used to indicate the goodness-of-fit between measured and descriptive results [16]. The implementation of goodness-of-fit statistics is done using the MATLAB program.

3.1 The Discrepancy Ratio (r_i)

$$r_i = \frac{|G^*|_p}{|G^*|_m} \tag{8}$$

where $|G^*|_p$ and $|G^*|_m$ are the descriptive and measured complex modulus, respectively. The subscript i denotes the dataset number. For a perfect fit, $r_i = 1$.

3.2 The Mean Normalized Error (MNE)

$$\text{MNE} = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{|G^*|_m - |G^*|_p}{|G^*|_p}\right| \tag{9}$$

where N is the total number of datasets and for a perfect fit, *MNE* = 0.

3.3 The Average Geometric Deviation (*AGD*)

$$\text{AGD} = \left(\prod_{i=1}^{N} R_i\right), \quad R_i = \begin{cases} |G^*|_p / |G^*|_m & \text{for } |G^*|_p \geq |G^*|_m \\ |G^*|_m / |G^*|_p & \text{for } |G^*|_p < |G^*|_m \end{cases} \tag{10}$$

where *AGD* = 1 for a perfect fit.

4.0 EXPERIMENTAL PROGRAMS

4.1 Materials

Various types of materials from the conducted experiments and the Nottingham Transportation Engineering Centre (NTEC) DSR database were used in this study. These include unaged and aged unmodified bitumens, polymer-modified bitumens (PMBs) and bitumen-filler mastics. 70/100 penetration grade bitumens were mixed with a plastomeric ethylene-vinyl acetate (EVA) polymer and an elastomeric styrene butadiene styrene (SBS) polymer to produce various polymer-modified bitumens. Three polymer contents (by mass) at 3, 5 and 7% were used to create several combinations of the EVA- and SBS- polymer-modified bitumens. Finally three different fillers namely gritstone, limestone and cement were mixed with 50 penetration grade bitumen at 40% (by weight) to produce various bitumen-filler mastics.

4.2 Dynamic Mechanical Analysis

The rheological properties of various materials were determined using dynamic mechanical methods consisting of temperature and frequency sweeps in an oscillatory-type testing mode performed within the LVE region. The oscillatory tests were conducted on a Bohlin Gemini dynamic shear rheometer (DSR) using two parallel plate testing geometries consisting of 8 mm diameter plates with a 2 mm testing gap and 25 mm diameter plates with a 1 mm testing gap (Figure 4). In this study, the samples were prepared using a hot pour method and a silicone mould method.

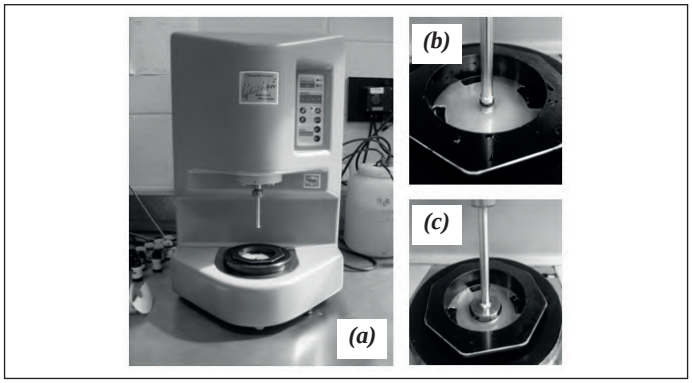


Figure 4: (a) The DSR body, (b) the 8 mm plates and (c) the 25 mm plates

In the hot pour method, the gap between the upper and lower plates was set to a desired height of 50 μm plus the required testing gap, either at the proposed testing temperature or at the mid-point of an expected testing temperature range. Once the gap has been set, a sufficient quantity of hot bitumen (typically between 100 – 150°C) was poured onto the lower plate of the DSR to ensure a slight excess of material appropriate to the chosen testing geometry. The upper plate of the DSR was then gradually lowered to the required nominal testing gap plus 50 μm. The bitumen that has been squeezed out between the plates was then trimmed flush to the edge of the plates using a hot spatula or blade. After trimming, the gap was closed by a further 50 μm to achieve the required testing gap as well as a slight bulge around the circumference of the testing geometry (periphery of the test specimen) [17].

Meanwhile, for the silicone mould method, the hot bitumen is poured into either an 8 mm or 25 mm diameter silicone mould of height approximately 1.5 times that of the recommended testing gap for the two geometries, namely 3 mm and 1.5 mm for the 8 mm and 25 mm geometries. The testing gap is set at a height of 50 μm plus 1 mm or 2 mm. Once the bitumen has cooled, either by means of short-term refrigeration or by natural cooling, the bitumen disc (typically at ambient temperatures) is removed from the mould and centred on the lower plate of the DSR. The upper plate is then lowered to the required gap plus 50 μm, the excess bitumen is trimmed with a hot spatula and the gap further closed to its final testing height [17].

Amplitude sweep tests are first conducted to determine the LVE region of the bituminous binders based on the point where $|G^*|$ has decreased to 95% of its initial value [18]. After obtaining the limiting strain, frequency sweep tests are carried out under the following test conditions:

Mode of loading	:	controlled-strain
Temperatures	:	10 to 80 °C (with the interval of 5 °C)
Frequencies	:	0.01 to 10 Hz
Spindle geometries	:	8 mm (diameter) and 2 mm gap (10 to 35 °C) and 25 mm (diameter) and 1 mm gap (25 to 80 °C)
Strain amplitude	:	within the LVE response, dependent on $\|G^*\|$ of each material used

For the construction of the $|G^*|$ and δ master curves, T_{ref} is arbitrarily taken at 10 °C. The curve is shifted manually, without assuming any shift factor forms.

4.3 Ageing Procedures

Short- and long-term laboratory ageing of the unmodified bitumens and polymer-modified bitumens were performed using the Rolling Thin Film Oven Test (RTFOT, ASTM D 2872) and the pressure ageing vessel (PAV, AASHTO PP1) respectively. The standard ageing procedures of 163 °C and 75 min for the RTFOT and 100 °C, 2.1 MPa and 20 h for the PAV were used. Meanwhile, the Thin Film Oven Test (TFOT, ASTM D1754) was used to age the bitumen-filler mastics at 1, 3, 5, 10 and 20 hours of ageing times. All the aged binders then subjected to DMA to evaluate changes in their rheological properties [18-19].

5.0 RESULTS AND DISCUSSION

5.1 Unaged Unmodified Bitumens

Table 1 shows the parameters (or constants) of the model used for simulation on different penetration grades of unaged unmodified bitumens. The materials tend to show Newtonian behaviour at high temperatures with G_o equal to zero, and therefore only six parameters of the model are needed to be determined. Interestingly, four of the model's parameters (G_∞, G_o, k and h) are found to be the same for all samples, regardless of the source of the crude and penetration grade bitumens. In this study, for simplification, G_∞ is taken as 1 GPa, as suggested for most engineering practical purposes [5]. Other parameters (α, β, τ, k and h) are determined iteratively to achieve the best fit based on the measured dynamic shear data.

Table 1: Parameters of the 2S2P1D model for unaged unmodified bitumens

Pen Grade	G_o (Pa)	G_∞ (GPa)	k	h	α	τ (x10^{-4})	β
10/20	0	1.00	0.22	0.64	5.00	60.00	90
35/50	0	1.00	0.22	0.64	4.00	15.00	75
40/60	0	1.00	0.22	0.64	3.50	3.00	90
70/100	0	1.00	0.22	0.64	3.00	0.50	90
160/220	0	1.00	0.22	0.64	2.30	0.35	45

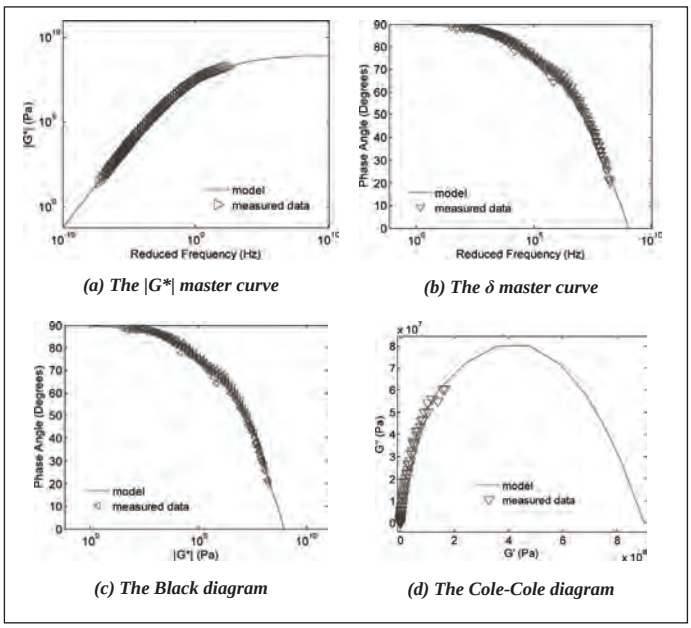
It is found that β for 10/20, 40/60 and 70/100 penetration grade bitumens is the same due to the fact that they have the same gradient at high temperatures. 160/220 penetration grade bitumen shows the lowest value of β. τ varies significantly for all materials, which shows that τ is time dependent. α decrease linearly from 10/20 penetration grade bitumen to 160/220 penetration grade bitumen. Di Benedetto and co-workers [12-13] show that α is approximately equal to 2.30 and consistent for all materials. It is believed that this phenomenon can be attributed to the fact that DSR data are affected by testing errors, particularly at high temperatures. Moreover, the different equipment used by the respective researchers may play a significant role in the data precision.

For a comparison between the measured and descriptive $|G^*|$ and δ master curves, the Cole-Cole diagram and the Black diagram are shown in Figure 5. For brevity, only 35/50 penetration grade bitumen is shown here with the understanding that the commentaries apply to all other conventional bitumens.

The 2S2P1D model is able to fit reasonably well with the measured $|G^*|$ and δ data. The Black and Cole-Cole diagrams show that the unaged unmodified bitumen data are consistent and can therefore be classified as the thermo-rheological simple materials. It is inferred that the 2S2P1D model is able to describe the rheological properties of unaged unmodified bitumens satisfactorily.

5.2 Unaged Bitumen-Filler Mastics

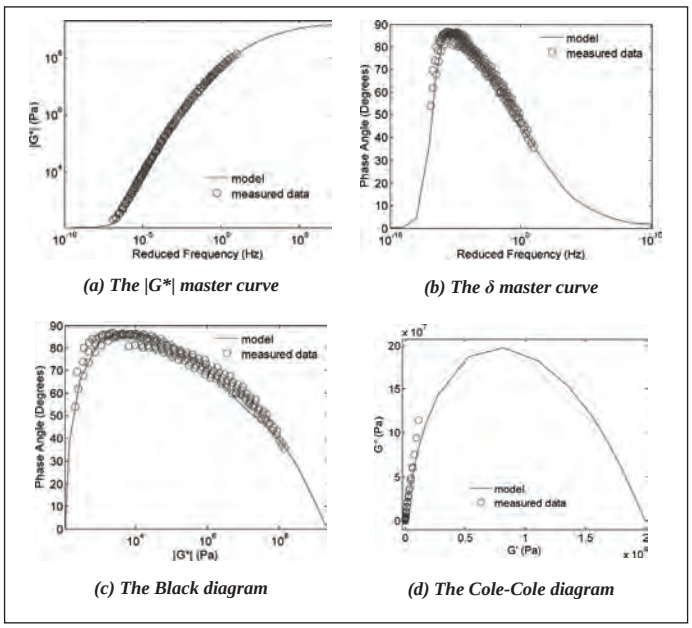
Mastics, composed of bitumen and filler, is an intermediate material between bitumen and asphalt mixture [19-20]. The presence of filler cannot therefore be neglected and have important effects such as improving the surface area, strength, plasticity, amount of voids, resistance to water action and



(a) The |G| master curve* *(b) The δ master curve*

(c) The Black diagram *(d) The Cole-Cole diagram*

Figure 5: A comparison between the measured and descriptive data of unaged unmodified bitumen



(a) The |G| master curve* *(b) The δ master curve*

(c) The Black diagram *(d) The Cole-Cole diagram*

Figure 6: A comparison between the measured and descriptive data of unaged bitumen-filler mastics

resistance to weathering [20]. Three different types of fillers– cement, gritsone and limestone– are used in this study, and the parameters of the model used for simulation for each bitumen-filler mastic are shown in Table 2. In general, *k*, *h* and β respectively, are the same for all fillers studied. This indicates that all samples have the same gradient at high temperatures.

Table 2: Parameters of the 2S2P1D model for bitumen-filler mastics

Material	G_o (Pa)	G_∞ (GPa)	*k*	*h*	α	τ (x10^{-4})	β
Gritstone	600	4.00	0.21	0.55	4.00	1.10	250
Limestone	10	2.00	0.21	0.55	4.00	4.00	250
Cement	120	2.00	0.21	0.55	4.00	3.00	250

The presence of filler mastics can be observed where G_∞ is higher than for the unaged unmodified bitumens and G_o should not be taken as zero. Delaporte *et al.* [13-14] report that this phenomenon can be attributed to the existence of solid contacts between particles. The results show that G_o for cement and gritstone bitumen-filler mastics are an order of magnitude greater of 1 and 2 respectively than the limestone bitumen-filler mastics. Among these fillers, limestone and cement are basic fillers, whereas gritstone is acidic, therefore the gritstone bitumen-filler mastic shows higher $|G^*|$ values at both higher and lower temperatures.

For a comparison between the measured and descriptive $|G^*|$ and δ master curves, the Cole-Cole and Black diagrams for unaged cement bitumen-filler mastic are shown in Figure 6. Like unaged unmodified bitumens, the 2S2P1D model shows a good correlation with the measured $|G^*|$ and δ data. At low frequencies, the δ master curve increases until it reaches the pinnacle point. δ decrease as the frequencies decreases and the filler shows a dominant role in the mixture's stiffness. The effects of fillers are shown where the measured data are slightly scattered in the Black and Cole-Cole diagrams. However, the 2S2P1D model is still able to satisfactorily describe the rheological properties of the bitumen-filler mastics.

5.3 Unaged Polymer-Modified Bitumens

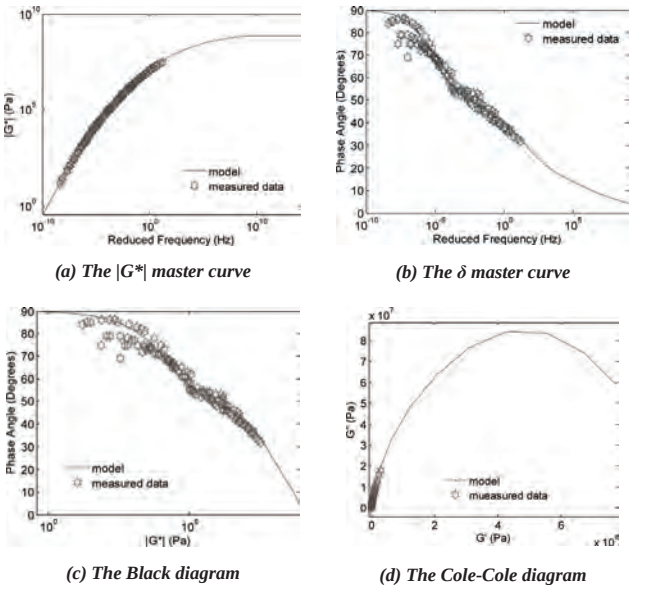
Table 3 shows the parameters of the model used for the simulation of unmodified (control sample) and polymer-modified bitumens. Two type of polymers– etylene-vinyl-acetate (EVA) and styrene-butadiene-styrene (SBS) – are mixed with the 70/100 penetration grade bitumen at different percentages. As suggested by Lu *et al.* [21], the value of G_∞ can be taken as 1 GPa for polymer-modified bitumens. The parameters (G_∞, G_o, *k* and *h*) are the same for one polymer-modified bitumen compared to the other, but α, τ and β vary. A similar observation has been made for the control sample. As shown in Table 3, α is inconsistent between the control sample and the EVA- and SBS-modified bitumens. This could be attributed to the fact that where data at high frequencies and/or low temperatures are exposed to testing errors. For bitumen modification, α is more consistent for the SBS-modified bitumen compared to the EVA-modified bitumen. This is probably due to the fact that the presence of the EVA semi-crystalline structure at different temperatures increases the complexity of the bitumens. A thorough discussion of the rheological properties of EVA- and SBS-modified bitumens can be found in previous publications [17-18, 22-24].

Table 3: Parameters of the 2S2P1D model for EVA and SBS-modified bitumens

Percent	Modifier	G_o (Pa)	G_∞ (GPa)	*k*	*h*	α	τ (x10^{-4})	β
0	Unmodified	0	1.00	0.21	0.55	3.50	0.50	150
3	EVA	0	1.00	0.21	0.55	3.50	0.50	600
5		0	1.00	0.21	0.55	3.00	0.60	1000
7		0	1.00	0.21	0.55	2.30	0.60	6000
3	SBS	0	1.00	0.21	0.55	2.30	0.30	1500
5		0	1.00	0.21	0.55	2.30	0.30	3000
7		0	1.00	0.21	0.55	2.30	0.50	20000

Meanwhile, β increases as the percentage of modifier is increased. The presence of polymer modification increases the viscosity of the mixtures. Figure 7 shows an example of $|G^*|$ and δ master curves, the Black and Cole-Cole diagrams for 7% EVA-modified bitumen. The 2S2P1D model shows a good correlation with the measured $|G^*|$. However, this model is unable to show a good fitting with the measured δ where data are dispersed particularly between 65 and 85°. Similarly, the Black diagram shows that the model deviates from the measured data. The Cole-Cole diagram shows a good correlation between the measured and descriptive data. However, more data at low temperatures are needed for a better graphical representation in that diagram.

Olard and Di Benedetto [12] discovered an identical problem where a breakdown of the time-temperature superpostion principle (TTSP) above 10 °C is observed for polymer-modified bitumens. They classify this property as the partial time-temperature superposition principle (PTTSP), as the shifting procedure gives a continuous master curve only for $|G^*|$. The introduction of the PTTSP appears to be an alternative to the concept of thermo-rheologically complex (not thermo-rheological simple) behaviour of materials [12].



(a) The $|G^*|$ master curve *(b) The δ master curve*

(c) The Black diagram *(d) The Cole-Cole diagram*

Figure 7: A comparison between the measured and descriptive data of unaged polymer-modified bitumens

5.4 Aged Unmodified Bitumen

The existence of an important change in behaviour due to binder ageing has been observed mainly at higher temperatures and/or lower frequencies. Table 4 shows the parameters of the model used for simulation for unaged (control sample) and aged unmodified bitumens. The parameters (G_∞, G_o, k and h) are the same for the unaged and aged samples. β that links to the Newtonian viscosity η of the 2S2P1D model has a large influence at high temperatures [12]. Ageing mainly affects β. Ageing adsorbs the asphaltenes and renders the bitumens stiffer. The values of β increase from unaged to aged unmodified bitumens. This affects the dynamic shear data by an increase in $|G^*|$ data at high temperatures and decreases δ. Meanwhile α also increases from unaged to aged materials. Delaporte *et al.* [13] discovered the same finding, where α increases from 2.3 to 3.0 when comparing the $|G^*|$ master curves of unaged and aged unmodified 50/70 penetration grade bitumen. Therefore, α can be used as an "ageing indicator", where a higher value of α indicates that the materials are susceptible to ageing.

Table 4: Parameters of the 2S2P1D model for aged unmodified bitumen

Method*	G_o (Pa)	G_∞ (GPa)	k	h	α	τ (x10^{-4})	β
Unaged	0	1.00	0.21	0.55	3.50	0.50	150
RTFOT	0	1.00	0.21	0.55	5.00	0.50	400
PAV	0	1.00	0.21	0.55	5.00	4.00	1500

RTFOT: Rolling Film Thin Oven Test, PAV: Pressure Vessel Ageing

5.5 Aged Bitumen-Filler Mastics

An attempt has also has been made to model aged bitumen-filler mastics using the 2S2P1D model (Table 5). However, the cement bitumen-filler mastics data from Wu's study [19] are inconsistent and therefore the experimental results have been discarded.

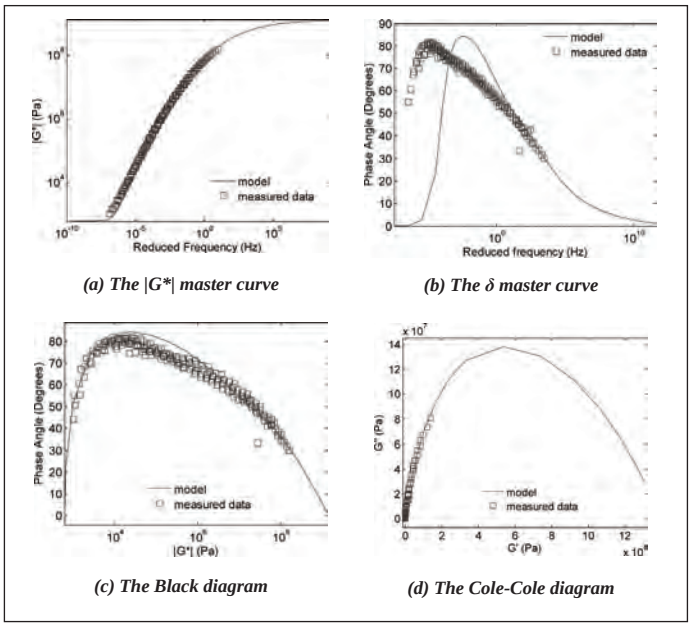
Table 5: The model parameters for aged bitumen-filler mastics

Material	Time (h)	G_o (Pa)	G_∞ (GPa)	k	h	α	τ (x10^{-4})	β
Gritstone	1	200	1.40	0.21	0.55	2.30	9.50	150
	3	12000	1.60	0.21	0.55	2.30	6.00	150
	5	8000	1.70	0.21	0.55	2.30	8.00	150
	10	600	1.40	0.21	0.55	2.30	20.00	150
	20	600	1.00	0.21	0.55	2.30	100.00	600
Limestone	1	8	1.50	0.21	0.55	2.30	5.50	150
	3	10	1.50	0.21	0.55	2.30	8.00	150
	5	10	1.50	0.21	0.55	2.30	10.00	150
	10	10	1.20	0.21	0.55	2.30	20.00	150
	20	3000	1.30	0.21	0.55	2.30	20.00	800

The gritstone and limestone bitumen-filler mastics yield the same values of parameters (k, h, δ and β) for ageing times from 1 to 10 hours. However, as the ageing time increases up to 20 hours, β increases up to 600 for gritstone bitumen-filler mastic and 800 for limestone bitumen-filler mastic respectively. Like unaged bitumen-filler mastics, G_o cannot be taken as zero due to the existence of solid contacts between particles. The acidic gritstone bitumen-filler mastic shows a big difference in G_∞ with ageing times compared to the limestone bitumen-filler mastic. In his work, Wu [19] shows that $|G^*|$ for gritstone bitumen-filler mastic increases as the ageing time increases. However, an initial reduction is observed for $|G^*|$ (at higher temperatures) of the limestone bitumen-filler mastic with the lowest value after one hour of ageing time. This phenomenon is believed to be caused by the adsorption of heavier fractions from bitumen to the mineral surface of the limestone bitumen-filler mastics [19].

As an example of aged cement bitumen-filler mastics $|G^*|$ and δ master curves, the Black and Cole-Cole diagrams are shown in Figure 8. The 2S2P1D model correlates well with the measured $|G^*|$ but shows a poor correlation with the measured δ. A similar observation is made in the Black diagram, where this model shows a slight deviation from the measured δ between

70 and 85°. However, the Cole-Cole diagram shows a good correlation between the measured and descriptive data. The PTTSP principal can also be implemented on aged bitumen-filler mastics where the shifting procedure gives a continuous master curves only for $|G^*|$.



(a) The |G| master curve* *(b) The δ master curve*

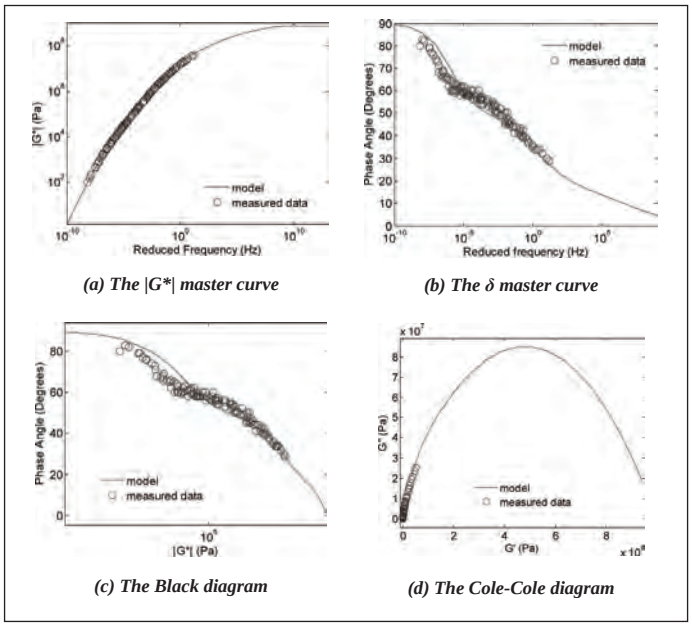
(c) The Black diagram *(d) The Cole-Cole diagram*

Figure 8: A comparison between the measured and descriptive data of aged bitumen-filler mastics

5.6 Aged Polymer-Modified Bitumens

The parameters used for simulation on the aged polymer-modified bitumens are shown in Table 6. G_∞, G_o, k and h respectively are consistent between one material and the other. β increases as the percentage of modifications is elevated. However, for certain samples, the changes of α depend on the percentage of modifications used. It is believed that the values of α from RTFOT- to PAV-aged materials are affected by the hardness of the samples and also ageing itself.

Figure 9 shows an example of the $|G^*|$ and δ master curves, the Black diagram and Cole-Cole diagram for aged 7% SBS-modified bitumen. Airey [9] found that the effect of ageing can be seen as an alteration of the Black diagram "waves" associated with the different crystalline structures and a general reduction in polymer modification. Meanwhile, the effect of ageing on the polymer-dominant regions for SBS-modified bitumen relate to a shifting of the rheological properties towards a greater viscous response as a result of the thermo-oxidative degredation of SBS-modified bitumen [9]. Therefore, the PTTSP is implied for aged polymer-modified bitumens.



(a) The |G| master curve* *(b) The δ master curve*

(c) The Black diagram *(d) The Cole-Cole diagram*

Figure 9: A comparison between the measured and descriptive data of aged polymer-modified bitumens

5.7 Goodness-of-fit

Tables 7 and 8 show the goodness-of-fit statistics between the measured and descriptive data of $|G^*|$ and δ. The discrepancy ratio r_i is used to observe the descriptive data's tabulation from the equality line, with a perfect value equal to one. When the r_i is larger or smaller than one, it measures how much wider the prediction interval has to be to cover the observed number of cases. With the interval of ±4% used in this study, the unaged unmodified bitumen data are dispersed closely to the equality

Table 6: The model parameters for aged EVA and SBS-modified bitumens

Method	%	Modifier	G_o (Pa)	G_∞ (GPa)	k	h	α	τ (x10^{-4})	β
RTFOT	3	EVA	0	1.00	0.21	0.55	4.50	1.00	1500
	5		0	1.00	0.21	0.55	5.00	3.00	2000
	7		0	1.00	0.21	0.55	5.00	2.00	10000
PAV	3		0	1.00	0.21	0.55	7.00	5.00	2500
	5		0	1.00	0.21	0.55	7.00	20.00	3000
	7		0	1.00	0.21	0.55	7.00	20.00	10000
RTFOT	3	SBS	0	1.00	0.21	0.55	4.00	0.30	1800
	5		0	1.00	0.21	0.55	5.00	0.15	8000
	7		0	1.00	0.21	0.55	5.00	0.30	8000
PAV	3		0	1.00	0.21	0.55	5.00	1.00	6000
	5		0	1.00	0.21	0.55	5.00	0.30	5000
	7		0	1.00	0.21	0.55	5.00	3.00	8000

RTFOT: Rolling Film Thin Oven Test, PAV: Pressure Vessel Ageing

line, followed by aged unmodified bitumens, unaged bitumen-filler mastics, aged filler mastics and aged polymer-modified bitumens. As expected, the unaged polymer-modified bitumens show the least correlation between the measured and descriptive $|G^*|$ data.

Like r_i, the MNE and AGD are also used to observe the difference between the measured and descriptive data. The unaged unmodified bitumens show the most outstanding correlation, with MNE = 8.73 and AGD = 1.09 for $|G^*|$ and MNE = 1.79 and AGD = 1.02 for δ respectively, followed by the aged unmodified bitumens, unaged bitumen-filler mastics, aged polymer-modified bitumens, aged bitumen-filler mastics and unaged polymer-modified bitumens. The presence of high asphaltenes in aged bitumen-filler mastics and polymer-modified bitumens renders a breakdown in TTSP. The materials are classified as the thermo-rheological complex materials. Additionally, ageing might possibly affect the breakdown in polymer structure, therefore decreasing the effect of the polymer-rich phase network in the mixtures.

6.0 CONCLUSION

The following conclusions are drawn from this study:

i. The 2S2P1D model is quite simple in its formulation, as a combination of springs, dashpot and parabolic elements. The calibration of the model is not a very difficult tasks provide very good modelling for unmodified and modified bitumens over a wide range of frequencies and temperatures.

ii. It is observed that this model is able to fit the rheological properties of unmodified bitumens (unaged and aged), bitumen-filler mastics (unaged and aged) and polymer-modified bitumens (aged). However, the model failed to fit the rheological properties of unaged polymer-modified bitumens particularly with high modifications. The fit is even worse when a comparison is made for measured and descriptive δ.

iii. For modelling purposes, the G_g values can be taken as 1 X 10^9 Pa for unmodified and polymer-modified bitumens, both unaged and aged samples. They approach a limiting maximum modulus at very low temperatures.

iv. For the unaged and aged bitumen-filler mastics, the G_g values vary. The G_g values depend on the percentage and a type of mineral fillers used. This phenomenon occurs due to the existence of physical interaction in the mixture. ■

Table 7: Goodness-of-fit for complex modulus data

Sample	Condition	Discrepancy ratio, r_i					AGD	MNE
		0.96-1.04	0.92-1.08	0.88-1.12	0.84-1.16	0.80-1.20		
Unmodified bitumen	unaged	26.43	48.87	72.10	87.78	96.27	1.09	8.73
	aged	39.29	64.88	75.00	80.51	82.89	1.09	9.42
Bitumen-filler mastics	unaged	25.30	47.82	65.55	76.31	84.93	1.12	11.32
	aged	12.62	25.00	35.27	45.55	57.30	1.21	19.20
Polymer-modified bit	unaged	13.69	29.46	41.43	51.13	59.05	1.25	25.63
	aged	17.37	35.19	50.19	62.75	71.96	1.16	16.03

Table 8: Goodness-of-fit for phase angle data

Sample	Condition	Discrepancy ratio, r_i					AGD	MNE
		0.96-1.04	0.92-1.08	0.88-1.12	0.84-1.16	0.80-1.20		
Unmodified bitumen	unaged	88.81	98.96	99.91	100.00	100.00	1.02	1.79
	aged	71.28	90.63	98.96	100.00	100.00	1.03	3.06
Bitumen-filler mastics	unaged	61.06	81.79	91.05	96.03	97.48	1.06	5.50
	aged	40.10	69.31	87.50	92.39	93.94	1.11	10.40
Polymer-modified bit	unaged	36.81	65.16	76.47	83.80	89.10	1.11	12.89
	aged	40.57	67.69	85.03	93.60	96.73	1.07	6.74

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EVALUATING DRIVER PERCEPTION TO THE EFFECTIVENESS OF INTEGRATED TRANSPORT INFORMATION SYSTEM (ITIS): AN ORDERED LOGIT APPROACH

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ABSTRACT

This study aims to investigate driver perceived effectiveness to the implementation of traffic information dissemination system, i.e. Integrated Transport Information System (ITIS) in Klang Valley region, Malaysia. Five evaluation indicators are chosen, namely usefulness, accuracy, reliability, satisfaction, and benefits of travel time saving. Using revealed preference study, drivers are asked to evaluate the system's effectiveness based on these indicators. The level of awareness and utilisation of the system is studied as well. Ordered logit models are developed to analyse the significant contributing factors to the perceived effectiveness. Results indicate that drivers perceived radio as the most effective tool. Although some of them perceived negatively to the accuracy and reliability of the system, about 56% of them commented that the system is useful while most of them anticipated that the current system could be further improved in the future.

1.0 INTRODUCTION

Nowadays, it is generally accepted that traffic congestion could not be alleviated through construction of more highways. From the demand and supply point of view, better management of road traffic through the implementation of the Intelligent Transportation System (ITS) is highly regarded as a more economic and effective alternative. Advanced Traveler Information System (ATIS) that disseminates traffic information aims to change the driver traveling decision in order to achieve better and more efficient transportation facility and resource allocation. Two types of traffic information could be disseminated, namely pre-trip information and en-route information. Pre-trip information can be disseminated through radio, internet, and TV which aims to affect the mode choice and departure time choice of travelers. The en-route information could be disseminated through radio and variable message signs (VMS) which is normally real time traffic information which aim to help drivers in avoiding traffic congestion by adjusting their route choice.

There are many existing studies that pertaining to the evaluation of the effectiveness of ATIS. Nevertheless, these studies share some limitations. First, most of the studies focused on investigating the awareness and utilisation of ATIS information. To name a few: in US, Peng and Guequierre [1] found that the awareness of VMS information is affected by the frequency of drivers encountering VMS signboards, the drivers' thrust on the information provided, and the drivers perceived usefulness of VMS information. Mannering *et al.* [2] found that males are less likely to perceive traffic information as important and the factors affecting awareness level are: drivers' socio economic characteristics, habitual travel pattern, congestion levels and attitude towards technology. In terms of utilisation, Spyridakis *et al.* [3] carried out a study on drivers' route choice behavior in Seattle, US. They found that drivers are more likely to divert to known routes and more willing to change their routes from work than from home. The willingness of drivers in route changing is affected by traffic message delivered, traffic congestion level, time of day, weather and time pressure. In Los Angeles, US, Abdel-Aty *et al.* [4] found that male drivers are more risk prone and willing to change route, commuters value and use pre-trip information more than en-route, drivers who perceived higher information reliability more prone to route change, and drivers on longer distance tend to choose alternative roads. However, these studies could only measure the system's effectiveness in an indirect way. They could not explain how drivers perceived the quality of the services and the value of the information provided. As the service provider, it is crucial to understand driver opinion and experience pertaining to the system which could help enhancing the services for better future market penetration. Second, most studies tend to focused on VMS (for example, [1] and [5]) and little research study has been carried out for other ATIS tools.

Nonetheless, the effectiveness of the overall ATIS system should not be represented by the popularity of only one tool. How other tools being utilised could also affect the overall system's effectiveness and thus vital to give due consideration to them. Third, there is little study for Malaysian cities. Although the ITIS system was developed in the Klang Valley region since year 2005, there is no research studies carried out to investigate the effectiveness of the system. Only recently, Roshandeh and Che-Puan [6] carried out a field study on VMS and found that the travel time could be reduced by 19.7% and the occupancy is shortened by 5.3%. However, more studies are necessary in order to understand the drivers' response and behavior towards the system besides learning the limitations of the system. One should not assume that drivers in Klang Valley will behave similarly as those who lived in other cities. This is simply because the living status and style, the educational background and the new technology acceptance of travelers could be different.

The objective of this study is to investigate the effectiveness of the traffic information dissemination system (such as radio, internet, and variable message sign) in the Klang Valley region, Malaysia, from the view point of drivers. Accordingly, a revealed preference questionnaire study is carried out to interview the drivers in the region in order to collect their opinion and comments on the system. Five important indicators are chosen to quantify the effectiveness of the system, namely the usefulness, accuracy, satisfaction, reliability, and travel time saving. Drivers are required to rate the performance of the system in a 5-scale Likert scale based on these indicators. In addition, the awareness and utilisation of traffic information is surveyed as well. It is expected that drivers' perceived effectiveness of the system is highly related to how drivers aware and utilise the information provided. The level of awareness is expressed in terms of frequency the traffic information is obtained via various traffic information tools while the level of utilisation is measured in terms of driver adjustments to the departure time or route for a trip. The findings from the questionnaire are analysed by developing the ordered logit models. The factors significantly affecting the perceived effectiveness are studied. Besides, the relationship among the effectiveness, awareness and utilisation are investigated. It is anticipated that this study could provide a comprehensive understanding of the traffic information system as well as the driver response to the system.

2.0 STUDY AREA

The study area chosen for this study is the Klang Valley region, which comprises Kuala Lumpur (the capital of Malaysia) and its neighboring sub-urban cities and towns. The region is located in the state of Selangor and is the nation's main industrial and commercial region. Over the years, the region has achieved strong economic growth compared to other states in Malaysia and such performance has attracted migration from other states. Population in the region has grown from 4 million in 2004 to 6 million in 2007. Along with the growth in economy and increase in population size, the private vehicle population has also increased by about 150%, from 2.2 million in 1996 to 5.5 million in 2008. About 55% of these vehicles are private cars, 35% motorcycles, 0.37% buses, 0.59% taxis, 5% trucks and 4% other types of vehicle [7]. Use of private transportation has also increased and the modal split of private vehicles to public transportation has changed from 75%:25% in 1985 to 84%:16% in 2006. The increased use of automobiles has resulted in traffic congestion in the region, causing average traffic speeds on the major roads being reduced to a critical level.

In 2005, the government has decided to develop a traffic information system to help improving the current traffic management system in the Klang Valley region. The Integrated Transport Information System (ITIS) developed by the City Hall Kuala Lumpur (CHKL), the governing authority of the region, is a combination of the existing Advanced Traffic Management System (ATMS) and Advanced Traveler Information System (ATIS). The ITIS collect traffic data from the detectors and closed circuits television cameras installed on the roadways. It is also equipped with the automatic incident detection system to detect the occurrence of unexpected incidents. Transport Management Centre (TMC) is set up to process, manage and analyse the traffic data. The centre will then disseminate the updated near-real time traffic information to drivers in the region.

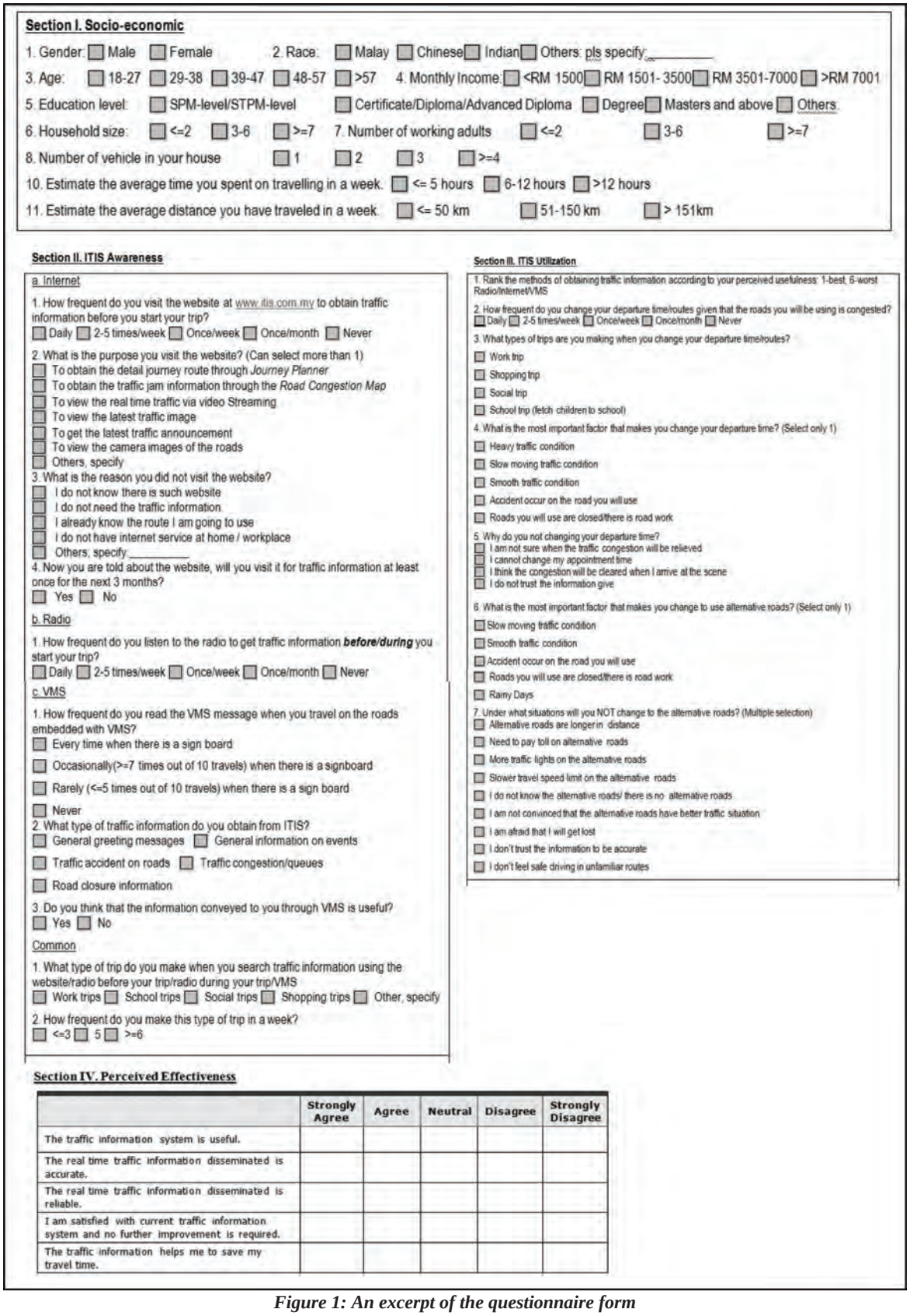
Currently, the system covers all major roads in the Kuala Lumpur Federal territory. A total of over 200 km of roads, which cover 45 arterial roads, is monitored [8]. The system is developed with a cost of RM 365 million. This large-scale project involved the installation of over 250 closed-circuit television (CCTV) cameras for traffic monitoring at key intersections, 700 video-based vehicle detector stations, 140 variable message signs (VMS) and 1600 units of vehicle tracking units to serve as dynamic probes. There are various tools used in ITIS to disseminate traffic information. The most common tools are internet, radio, and VMS. The ITIS Portal [9] provides a lot of valuable traffic information. For example, *Congestion Map* provides the real time traffic situation on the roadways; *Journey Planner* provides the detailed route from an origin to a destination. Furthermore, users could obtain the real time traffic and latest traffic image via video streaming on the website. Recently, another website (*www.llmtraffik.com.my*) is set up by the Malaysia Highway Authority (MHA) to provide real-time traffic information on most of the expressways in the Klang Valley region. Besides the internet, one can also rely on either VMS or radio for updated traffic information. For example, myFM (101.8 Hz), one of the famous Chinese radio programmes, periodically reports traffic conditions in the region between 7am and 9am in the morning and between 5pm and 8pm in the evening daily.

3.0 METHODOLOGY

3.1 Questionnaire Survey Study

A revealed preference (RP) questionnaire survey was designed to investigate drivers' perceived effectiveness of the system. Besides, it also aims to probe the relationship between the level of awareness and utilisation of the system to the perceived effectiveness. An excerpt of the questionnaire is shown in Figure 1. The questionnaire comprises four sections. Section I is related to the socio-economic and travel characteristics of the drivers. Socio-economic characteristics include gender, race, age, monthly income, education level, household size, number of working adults and number of vehicles in the house. For the travel-related characteristics, respondents have to estimate their average weekly travel time and distance they spent on traveling each week. Section II of the questionnaire is divided into three sub-sections to study the awareness and the utilisation of the ITIS system, namely the internet, radio, and VMS. Questions asked in

each sub-sections include the frequency of the tool being used to obtain traffic information, the trip purpose, and the number of trips generated weekly. The respondents are then asked to provide reasons for not adopting any particular traffic dissemination tool. For radio, an additional question is asked to check if the respondent is aware of traffic information availability by other means (pre-trip and en-route). Section III of the questionnaire is related to the utilisation of traffic information on their travels. Utilisation of traffic information is tracked by checking if drivers have made changes in their departure time choice and/or route choice after receiving information from each tool. In the case where respondents chose not to make any adjustments after receiving the traffic information, they were asked to provide a reason. In Section IV, the respondents were asked about their



Section I. Socio-economic

1. Gender: ☐ Male ☐ Female 2. Race: ☐ Malay ☐ Chinese ☐ Indian ☐ Others: pls specify:_____
3. Age: ☐ 18-27 ☐ 29-38 ☐ 39-47 ☐ 48-57 ☐ >57 4. Monthly Income: ☐ <RM 1500 ☐ RM 1501- 3500 ☐ RM 3501-7000 ☐ >RM 7001
5. Education level: ☐ SPM-level/STPM-level ☐ Certificate/Diploma/Advanced Diploma ☐ Degree ☐ Masters and above ☐ Others
6. Household size: ☐ <=2 ☐ 3-6 ☐ >=7 7. Number of working adults ☐ <=2 ☐ 3-6 ☐ >=7
8. Number of vehicle in your house ☐ 1 ☐ 2 ☐ 3 ☐ >=4
10. Estimate the average time you spent on travelling in a week. ☐ <= 5 hours ☐ 6-12 hours ☐ >12 hours
11. Estimate the average distance you have traveled in a week. ☐ <= 50 km ☐ 51-150 km ☐ > 151km

Section II. ITIS Awareness

a. Internet

1. How frequent do you visit the website at www.itis.com.my to obtain traffic information before you start your trip?
☐ Daily ☐ 2-5 times/week ☐ Once/week ☐ Once/month ☐ Never
2. What is the purpose you visit the website? (Can select more than 1)
☐ To obtain the detail journey route through *Journey Planner*
☐ To obtain the traffic jam information through the *Road Congestion Map*
☐ To view the real time traffic via video Streaming
☐ To view the latest traffic image
☐ To get the latest traffic announcement
☐ To view the camera images of the roads
☐ Others, specify
3. What is the reason you did not visit the website?
☐ I do not know there is such website
☐ I do not need the traffic information
☐ I already know the route I am going to use
☐ I do not have internet service at home / workplace
☐ Others, specify:_____
4. Now you are told about the website, will you visit it for traffic information at least once for the next 3 months?
☐ Yes ☐ No

b. Radio

1. How frequent do you listen to the radio to get traffic information ***before/during*** you start your trip?
☐ Daily ☐ 2-5 times/week ☐ Once/week ☐ Once/month ☐ Never

c. VMS

1. How frequent do you read the VMS message when you travel on the roads embedded with VMS?
☐ Every time when there is a sign board
☐ Occasionally(>=7 times out of 10 travels) when there is a signboard
☐ Rarely (<=5 times out of 10 travels) when there is a sign board
☐ Never
2. What type of traffic information do you obtain from ITIS?
☐ General greeting messages ☐ General information on events
☐ Traffic accident on roads ☐ Traffic congestion/queues
☐ Road closure information
3. Do you think that the information conveyed to you through VMS is useful?
☐ Yes ☐ No

Common

1. What type of trip do you make when you search traffic information using the website/radio before your trip/radio during your trip/VMS
☐ Work trips ☐ School trips ☐ Social trips ☐ Shopping trips ☐ Other, specify
2. How frequent do you make this type of trip in a week?
☐ <=3 ☐ 5 ☐ >=6

Section III. ITIS Utilization

1. Rank the methods of obtaining traffic information according to your perceived usefulness: 1-best, 6-worst
Radio/Internet/VMS
2. How frequent do you change your departure time/routes given that the roads you will be using is congested?
☐ Daily ☐ 2-5 times/week ☐ Once/week ☐ Once/month ☐ Never
3. What types of trips are you making when you change your departure time/routes?
☐ Work trip
☐ Shopping trip
☐ Social trip
☐ School trip (fetch children to school)
4. What is the most important factor that makes you change your departure time? (Select only 1)
☐ Heavy traffic condition
☐ Slow moving traffic condition
☐ Smooth traffic condition
☐ Accident occur on the road you will use
☐ Roads you will use are closed/there is road work
5. Why do you not changing your departure time?
☐ I am not sure when the traffic congestion will be relieved
☐ I cannot change my appointment time
☐ I think the congestion will be cleared when I arrive at the scene
☐ I do not trust the information give
6. What is the most important factor that makes you change to use alternative roads? (Select only 1)
☐ Slow moving traffic condition
☐ Smooth traffic condition
☐ Accident occur on the road you will use
☐ Roads you will use are closed/there is road work
☐ Rainy Days
7. Under what situations will you NOT change to the alternative roads? (Multiple selection)
☐ Alternative roads are longer in distance
☐ Need to pay toll on alternative roads
☐ More traffic lights on the alternative roads
☐ Slower travel speed limit on the alternative roads
☐ I do not know the alternative roads/ there is no alternative roads
☐ I am not convinced that the alternative roads have better traffic situation
☐ I am afraid that I will get lost
☐ I don't trust the information to be accurate
☐ I don't feel safe driving in unfamiliar routes

Section IV. Perceived Effectiveness

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The traffic information system is useful.					
The real time traffic information disseminated is accurate.					
The real time traffic information disseminated is reliable.					
I am satisfied with current traffic information system and no further improvement is required.					
The traffic information helps me to save my travel time.					

Figure 1: An excerpt of the questionnaire form

opinion on the effectiveness of ITIS system. They are required to express in a Likert scale (strongly disagree to strongly agree, on a five-point scale) on the usefulness, accuracy, reliability, satisfactory, and benefit of travel time saving of the system.

The survey was conducted from October 2nd 2009 to December 31st 2009 in Klang Valley region. A team of 15 trained interviewers conducted their surveys at shopping malls, petrol kiosks, schools, and other facilities in the Klang Valley region. Target respondents are drivers with valid licenses with sufficient driving experiences. A total of 1,506 respondents were interviewed during this period. Table 1 shows the summary of the characteristics of the respondents.

Table 1: Characteristics of respondents

Variables	Category	Percentage	Variables	Category	Percentage
Gender	Male	51%	Household size	<=2	18%
	Female	49%		3-6	68%
Race	Malay	28%		>=7	14%
	Chinese	56%	Number of working adults in a household	<=2	56%
	Indian	15%		3-6	42%
Age	18-28	58%		>=7	2%
	29-38	24%	Vehicle ownership in a household	1	38%
	39-47	12%		2	32%
	48-57	5%		3	18%
	>57	1%		>=4	12%
Monthly income	<RM 1,500	33%	Average weekly travel time	<=5 hours	35%
	RM 1,501-3,500	49%		6-12 hours	46%
	RM 3,501-7,000	16%		>12 hours	19%
	>RM 7,001	2%	Average weekly travel distance	<=50 km	32%
Education level	SPM/STPM	23%		51-150 km	42%
	Diploma	26%		>151 km	26%
	Degree	44%			
	Master and above	3%			
	Others	5%			

3.2 Modelling Approach: Ordered Logit Models

Five criteria are listed to evaluate the perceived effectiveness of ITIS, namely: usefulness, reliability, accuracy, satisfactory, and travel time saving. Drivers are required to rate how agree are they on the performance of ITIS based on these criteria on a 5-scale Likert scale, ranging from strongly disagree to strongly agree. Hence, the responses are discrete ordered variables. Ordered probability models are a form of discrete outcome model that relate the dependent variables in an ordered discrete scale to independent variables which can be continuous or discrete. They are derived by defining an unobserved variable y^* that is used as a basis for modeling the ordinal data [10].

This unobserved variable is typically defined as a linear function for each observation such that:

$$y_i^* = \boldsymbol{\beta}\mathbf{X} + \varepsilon \tag{1}$$

where $\mathbf{X}$ is a vector of independent variables for observation i, $\boldsymbol{\beta}$ is a vector of estimable parameters and ε is a random disturbances. Accordingly, the observed ordinal data y_i for each of the observation is defined as:

$$y_i = \begin{cases} 0 & \text{if } z \le \mu_0 \\ 1 & \text{if } \mu_0 \le z \le \mu_1 \\ \dots & \\ N & \text{if } z \ge \mu_{N-1} \end{cases} \tag{2}$$

where μ are the thresholds that define y that associate to the integer ordering and N is the highest integer ordered response. The values of μ and $\boldsymbol{\beta}$ are estimated from the data using the econometric software, Nlogit. Logit models are obtained if the disturbance term, ε is assumed to be Gumbel distributed. Without any loss of generality, μ_0 in eqn. (2) can set to be zero. It is important to note that the $\boldsymbol{\beta}$ in eqn. (1) does not imply the effect of the changes of $\mathbf{X}$ on y_i. The effect of the changes should be checked based on the marginal effect computation. In this research study, 0 is awarded to the answer of strongly disagree, 1 for disagree, and so on where 4 is awarded for strongly agree.

The categorical variables adopted in this study, such as household size, weekly average traveling distance, frequency of exposure to ITIS information, and others are modeled as continuous variables in the logit models. It is an alternative way of modeling categorical variables besides representing them as the dummy variables. The choice of the modeling approach, however, would not affect the credibility of the results obtained. Interested readers could find more information from Green [10].

4.0 MODELING RESULTS AND ANALYSIS

Prior to the modeling, the drivers' perceived effectiveness obtained from the questionnaire is shown in Figure 2. It is observed that the percentage of drivers perceived ITIS as useful, accurate and reliable are 56%, 35%, and 40% respectively (by taking into consideration of those agree and strongly agree).

About 45% of the respondent perceives that the system could help to reduce travel time. However, only 17.9% of the respondent satisfies with the current system.

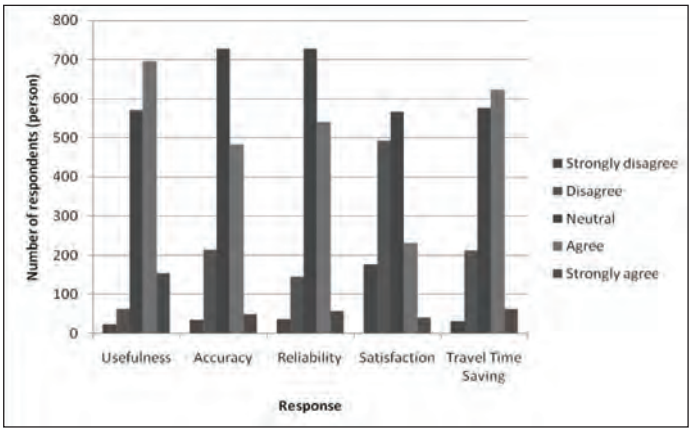


Figure 2: Respondents' perceived effectiveness of ITIS

4.1 Perceived Usefulness

The perceived usefulness describes driver opinion on how useful is the traffic information for their trips. This could include benefits obtaining from static information for trip planning and guidance as well as real time traffic information which help to avoid traffic congestion. Table 2 shows the ordered logit model for the drivers' perceived usefulness which is significant at 95% confidence level. The factors affecting the perceived usefulness are such as: attributes of drivers, travel characteristics, and types of ITIS tools.

Drivers with more number of adults in the household and with low vehicle ownership perceived the information to be more useful. This is reasonable as low vehicle ownership indicates that they need to share cars which resulted in requiring more traffic information for trip planning purposes. Drivers who have longer traveling distance perceived ITIS information as useful. This is because trip planning needs to be carried out for longer distance trip. Besides, drivers who perceived traffic information as useful are most likely to obtain information from radio. However, there is no relationship found between perceived usefulness and the level of traffic information utilisation.

Table 2: Ordered logit model for drivers' perceived usefulness

Variable	Coefficient	t-statistic
Constant	-5.635	0.000
Household size (0: <= 2; 1 :3-6; 2: >= 7)	0.211	2.045
Number of working adults in a household (0: <=2; 1: 3-6; 2: >=7)	-0.299	-2.624
Weekly average traveling distance (0: ≤ 50 km; 1: 51-150 km; 2: > 151 km)	0.200	2.185
Vehicle ownership in a household (0:1; 1:2; 2:3; 3: >= 4)	-0.175	-3.300
Frequency of listening to radio per-trip (0: Never; 1: Once/month; 2: Once/week; 3: 2-5 times/week; 4: Daily)	0.226	5.922
Log likelihood at convergence $\mu_1 = 1.32, \mu_2 = 3.93, \mu_3 = 6.45$	-1702	

4.2 Perceived Accuracy

The perceived accuracy describes driver experience on how accurate is the traffic information obtained compared to the real situation. This includes the estimated travel time and level of congestion disseminated by the system. Table 3 shows the model which is significant at 95% confidence level.

Driver socio-economic attribute has little impact on the perceived accuracy. All the three major races in the country perceived that the information is less accurate. Driver travel characteristics could also affect the perceived accuracy. Drivers who have longer travel distance in average perceived that the information is accurate. This is logic as drivers who have more frequent travel have higher probability to obtain and use the traffic information provided.

In addition, the level of awareness has certain impact. Drivers perceived that traffic information obtained from radio is more accurate than those obtained from VMS. Drivers who perceive the information to be accurate would prefer to change to alternative routes rather than changing their departure time.

Table 3: Ordered logit model for drivers' perceived accuracy

Variable	Coefficient	t-statistic
Constant	6.785	7.926
Race		
Malay (0: No; 1: Yes)	-2.722	-3.277
Chinese (0: No; 1: Yes)	-2.949	-3.564
Indian (0: No; 1: Yes)	-2.843	-3.399
Weekly average traveling distance (0: ≤ 50 km; 1: 51-150 km; 2: > 151 km)	2.325	2.544
Frequency of listening to radio per-trip (0: Never; 1: Once/month; 2: Once/week; 3: 2-5 times/week; 4: Daily)	0.187	4.999
Frequency of reading VMS messages (0: Never; 1: Rarely; 2: Occasionally; 3: Every time)	-0.107	-2.343
Departure time change (0: No; 1: Yes)	-0.373	-9.470
Route choice change (0: No; 1: Yes)	0.155	4.045
Restricted log likelihood	-1792.0	
Log likelihood at convergence	-1700.0	
$\mu_1 = 2.25, \mu_2 = 4.73, \mu_3 = 7.64$		

4.3 Perceived Reliability

The perceived reliability describes the trust of the drivers on the information obtained from the ITIS. This could affect their level of utilization of the information obtained. Table 4 shows the ordered logit model for the perceived reliability which is significant at 95% confidence level. Drivers' socio-economic characteristics have certain impact on the perceived reliability. It is found that male drivers perceived the information more reliable compared to female drivers. The three major races, i.e. Malay, Chinese, and Indian, in the country perceived the information as less reliable.

Besides, drivers with lesser number of vehicles in the household perceived the information more reliable. This shows that drivers appreciate the information disseminated for better trip planning in the case of car sharing. Besides, drivers

perceived that traffic information disseminated via internet and radio is reliable. Nevertheless, drivers who used to utilise ITIS information comment that the traffic information is less reliable.

Table 4: Ordered logit model for drivers' perceived reliability

Variable	Coefficient	t-statistic
Constant	6.358	7.398
Gender (0: Male; 1: Female)	-0.248	-2.466
Race **Malay (0: No; 1: Yes)** **Chinese (0: No; 1: Yes)** **Indian (0: No; 1: Yes)**	 -1.652 -1.669 -1.958	 -1.992 -2.024 -2.346
Vehicle ownership in a household (0:1; 1:2; 2:3; 3: >= 4)	-0.162	-2.990
Frequency of listening to radio per-trip (0: Never; 1: Once/month; 2: Once/week; 3: 2-5 times/week; 4: Daily)	0.163	4.332
Frequency of visiting ITIS Portal (0: Never; 1: Once/month; 2: Once/week, 3: 2-5 times/week; 4: Daily)	0.345	3.355
Departure time change (0: No; 1: Yes)	-0.157	-4.184
Route choice change (0: No; 1: Yes)	-0.123	-3.236
Restricted log likelihood **Log likelihood at convergence** $\mu_1 = 1.72$, $\mu_2 = 4.28$, $\mu_3 = 7.25$	-1741.2 -1705.7	

4.4 Perceived Satisfaction

Drivers are asked whether the current system conforms to their expectation and whether they satisfy about it. They are asked to comment whether further improvement is required for the system. Table 5 shows the ordered logit model for the perceived reliability which is significant at 95% confidence level. Household with low vehicle ownership and more working adults perceived higher level of satisfaction. This shows that drivers appreciate the information disseminated for better trip planning in the case of car sharing. Drivers who have shorter travel distance in a week perceived more satisfy to the system. This shows that they appreciate the system well for their travel planning.

Furthermore, drivers perceived satisfactory on the information disseminated via internet and radio. Drivers who satisfied with the system choose to change their departure time choice rather than route choice.

4.5 Perceived Travel Time Saving

This is to investigate whether drivers perceive that the traffic information obtained could help them save their travel time by making necessary adjustment to their trip. Table 6 shows the model which is significant at 95% confidence level. Females and those household with fewer vehicle ownership perceived positively towards the benefit of ITIS in travel time saving. Among the ITIS tools, drivers perceived that they could obtain valuable traffic information from radio.

In addition, drivers perceived that they could save travel time by changing their departure time rather than diverting to alternative routes. This explains that drivers feel unsecure in choosing alternative routes in which they are unfamiliar with.

Table 5: Ordered logit model for drivers' perceived satisfaction

Variable	Coefficient	t-statistic
Constant	3.881	4.423
Age (0: 18-27; 1: 29-38; 2: 39-47; 3: 48-57; 4: > 57)	-0.132	-2.475
Vehicle ownership in a household (0:1; 1:2; 2:3; 3: >= 4)	-0.204	-4.004
Number of working adults in a household (0: <= 2; 1: 3-6; 2: >= 7)	0.256	2.271
Weekly average traveling distance (0: ≤ 50 km; 1: 51-150 km; 2: > 151 km)	-0.228	-2.534
Frequency of visiting ITIS Portal (0: Never; 1: Once/month; 2: Once/week; 3: 2-5 times/week; 4: Daily)	0.298	3.204
Frequency of listening to radio per-trip (0: Never; 1: Once/month; 2: Once/week; 3: 2-5 times/week; 4: Daily)	0.224	6.093
Departure time change (0: No; 1: Yes)	0.252	6.583
Route choice change (0: No; 1: Yes)	-0.314	-8.144
Restricted log likelihood **Log likelihood at convergence** $\mu_1 = 1.88$, $\mu_2 = 3.79$, $\mu_3 = 5.95$	-2063.2 -1987.6	

In addition, they are uncertain on the traffic situation on the alternative routes.

Table 6: Ordered logit model for drivers' perceived travel time saving

Variable	Coefficient	t-statistic
Constant	3.415	4.304
Gender (0: Male; 1: Female)	0.229	2.334
Vehicle ownership in a household (0:1; 1:2; 2:3; 3: >= 4)	-0.225	-4.322
Frequency of listening to radio per-trip (0: Never; 1: Once/month; 2: Once/week; 3: 2-5 times/week; 4: Daily)	0.181	4.805
Departure time change (0: No; 1: Yes)	0.203	5.328
Route choice change (0: No; 1: Yes)	-0.083	-2.180
Restricted log likelihood **Log likelihood at convergence** $\mu_1 = 2.24$, $\mu_2 = 4.16$, $\mu_3 = 7.21$	-1839.5 -1792.3	

5.0 COMMENTS ON DRIVER PERCEIVED EFFECTIVENESS OF ITIS

From the models presented above, there are a few interesting results obtained. First, it is observed that the socio-economic background of the drivers has little influence on their perceived effectiveness of ITIS. Youngsters are more satisfy with the system while all three main races in the country perceived that the information is less accurate. Drivers who have lower number

of vehicle ownership in the household are desperately required more traffic information for their trip planning purposes due to car sharing with partners. Second, drivers who travel longer distance in average appreciate the deployment of the system. They perceived that ITIS is useful and the information delivered has high level of accuracy. Nonetheless, most of them think that there is still much room of improvement to the current system, such as to increase the information coverage area, and types of information disseminated. Third, radio is an important tool that can influence drivers' behavior especially before they start a trip. Drivers have great acknowledgement to the traffic information delivered through radio. They trust the information to be useful, accurate, reliable, and could help them save their travel time. In overall, they feel satisfied with radio. Besides, drivers perceived that the traffic information on ITIS Portal is reliable. They feel satisfy to the ITIS Portal, in terms of website user-friendliness, loading speed and easy understandable. The three major purposes of them visiting the website are to use the Journey Planner (42%) in order to find the best route for traveling, followed by viewing the Road Congestion Map to obtain updated traffic condition (19%), and to view the real time traffic via video streaming (18%). When asked the reasons why they did not visit the website, the main reason cited is unaware of its existence (70%). Respondents perceived that the information from VMS is inaccurate (25%), despite that VMS is a popular tool favored by drivers [11]. Forth, drivers prefer to adjust their departure time choice (either earlier or later) than changing to alternative routes. The adjusting rate for departure time choice and route choice are 26% and 24% respectively [11]. They chose to change their departure time if they are satisfied with the system and perceived that it could save their travel time. 74% of the respondents choose to change their departure time when they receive traffic information of heavy traffic condition, while the major reason cited for not changing is due to fixed arrival time (44%). They considered diverting to alternative routes if they perceived that the information as accurate. About 73% of the respondents are willing to divert to alternative routes if heavy traffic condition is reported. The three main factors that discourage them to do so are such as unconvinced of the traffic condition on the alternative roads (31%), tolls on alternative roads (15%), and lack of knowledge on network background (11%).

It could be seen that there is some relation among drivers' perceived effectiveness, level of awareness and level of utilisation. However, they are not necessarily positively or negatively related. Drivers would prefer to obtain the information from certain tool but not necessary perceived it to be the most effective one. In this case, VMS is the most popular tool preferred by drivers [11] but they perceived radio as the most effective tool. According to the drivers' post-experience on utilising the ITIS information, they commented that the information provided is less accurate and less reliable. In addition, the findings obtained in this study also show that the effectiveness of the ITIS could not be represented by the awareness of one type of tool or one type of response measured. Drivers might perceive some tools as inaccurate (VMS in this case) but have high recommendation on the other tool (radio in this case). Moreover, drivers might perceive the system as useful but reluctant to make changes to their trip due to some external effects. Thus, one should consider the performance of the overall system rather than a single component in measuring the effectiveness of the ITIS.

6.0 CONCLUSION

This paper has investigated the driver perceived effectiveness of the implementation of ITIS system in Klang Valley region, Malaysia. The perceived effectiveness is evaluated through five important performance indicators, namely usefulness, reliability, satisfaction, accuracy, and the benefit of travel time saving. A total of 1506 qualified drivers are interviewed. It is found that about 56% of the drivers perceived that the ITIS is useful and important for their trip planning, but only 17.9% of them satisfied with the current system. This means that ITIS has the potential to help in alleviating traffic congestion problem if the current system can be further improved. Besides, it is observed that drivers perceived negatively on the accuracy and the reliability of the system. This indicates that the current system has limitations and needs to be improved. Besides, drivers prefer to obtain traffic information from various tools of ITIS, as they perceived the effectiveness of these tools differently. They like to listen to radio for information, but have higher perceived reliability to information disseminated by internet (ITIS Portal). They might complaint that the information disseminated via VMS is less accurate but willing to pay more attention to its information. These findings indicate the complexity of driver perception and behavior to the ITIS system.

To improve the effectiveness of the current system, the authority could consider to extent their system by developing a dedicated radio channel specifically for traffic information dissemination purposes. Besides, the coverage area of the ITIS could be extended to some other roads in the region. It would be better if the advice on the alternative roads could be delivered to drivers traveling on the congested roads. On the other hand, the authority should consider seriously on the types of the message delivered through VMS. This is the concern with the dynamic traffic assignment in which whether actual or ideal route travel time should be provided. Some research studies are required in the future to look into this matter. The limitation of the current study is the uneven distribution of the respondents interviewed. It is observed that more than half of the respondents are youngsters (58%) and Chinese (56%). This could be a source of bias to the results obtained.

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PROFILE

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UV BASED PROCESS FOR *E.COLI* AND COLIPHAGE IN SECONDARY EFFLUENT FOR WASTEWATER RECLAMATION AND REUSE

(Date received: 21.09.10/Date accepted: 08.08.12)

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ABSTRACT

The persistency and survival of pathogenic contamination related to biological risk has been a public concern when implementing water reclamation and reuse. To secure the public health risk when implementing water reuse, adequate treatment is needed. In this study Ultraviolet (UV), based treatment was studied for the applicability to remove microorganisms from secondary effluent. E.coli, Qβ, T4 and Lambda phages were used as targeted microorganisms during the UV treatment process. The objectives of this study were to investigate the inactivation characteristics of E.coli, Qβ, T4 and Lambda phage to UV treatment process and investigate the effect of combine UV/H_2O_2 for E.coli and Qβ phage inactivation. As a result, T4 and Lambda phage from DNA group phage were found more resistant to UV treatment process compared to Qβ phage from FRNA phage group and E.coli from coliform group. Combined process UV/H_2O_2 in secondary effluent could increase the inactivation efficiency of E.coli and Qβ. DOC and UV 254 were found strongly affected the disinfection processes. Secondary effluent treated with UV processes was found suitable for wastewater reclamations.

Keywords: *E.coli; Lambda phage; Qβ; T4; UV; Wastewater*

1.0 INTRODUCTION

The concept of converting waste to resource is not a new concept. Waste from wastewater industry has been converted into useful resources [1]. At the source, grey water can be reused for toilet flushing as it is uneconomical to use treated water just to flush toilets [2]. Grey water reuse will reduce the demand for treated water. The reuse of effluent for irrigation purposes has occurred for centuries, and with increasing pressure on potable water supplies, the extent of reuse is increasing [3]. Secondary effluent can also be reused for toilet flushing purposes. Secondary effluent have been used for landscaping and general washing purposes as researchers have found the levels of faecal coliforms are acceptable [4-5]. The utilisation of secondary effluent for reclaimed wastewater also contributes in reducing potential negative impacts of wastewater discharges to receiving waters.

Over the past few years, interest in the existence of pathogens in reclaimed wastewater has rapidly increased with the increased in public awareness on human health and safety. The pathogenic microorganisms in treated wastewater for reclamation purposes pose potential health risks. It was found that apart from faecal coliforms, other pathogens have also been found in effluent, such as *Kliebsela spp.*, *Shigella spp.*, *Enterobacter spp.*, etc. [6]. Therefore, human health risk should be managed related to pathogenic microorganisms contained in the wastewater. In order to reduce biological risk from reclaimed wastewater, a few guidelines were developed.

- California State regulation [7] proposed less than 2 Total Coliform/100ml involved specified multi-steps treatment. Proposed regulation would add $\log_{10}$ microbes reduction levels for bacteria (6-logs) viruses (coliphages) (5-logs) and bacterial spores (*C.perfringens*) as protozoan parasite indicator (4-logs).
- US EPA regulation [8]: Proposed ≤ 200 FC/100ml for less stringent reclaimed water uses and 4-logs reduction of *Cryptosporidium* (22 mJ/cm^2), Giardia (22 mJ/cm^2) and virus (186 mJ/cm^2).
- WHO guidelines [9]: Proposed about 6-7 logs pathogen reduction for unrestricted agricultural uses, 3-4 logs for restricted irrigation and 2-4 logs for drip irrigation purposes.
- Australian Guideline for Water Reuse [10]: This guideline proposed reduction of bacteria (5-logs), virus (6.5-logs), protozoa (5-logs), helminth (5-logs) recommended for Class A+ (dual- reticulation system). Further, reduction of bacteria (8-logs), virus (9.5-logs), protozoa (8-logs), helminth (8-logs) for augmentation of drinking water supplies.
- Malaysian Sewerage Industry Guidelines [11] stipulated that continuous disinfection is required for sewage treatment plants serving more than 20,000 population equivalent (PE) discharging into bathing or recreation waters. For continuous disinfection, Chlorination, UV or Ozone is recommended.

Other sewage treatment plants are to be equipped with dosing tank structure capable of intermittent disinfection facilities and only chlorination is recommended.

The guidelines were developed to ensure the reclaimed water is safe enough and reliable to be used by consumers. In order to attain adequate water quality standard, appropriate treatment is needed. Disinfection process is considered as the last barrier to control pathogenic microorganisms in reclaimed wastewater. However, secondary treatment and chlorination are insufficient to inactivate persistent microorganisms like viruses and protozoa. Therefore, an advanced technology is necessary to consider for achieving high reclaimed water quality.

There are many countries that have even implemented the effluent reuse up to potable water quality. Singapore implemented the production of NEWater (potable quality effluent reuse), initiated in 1998 to supplement Singapore's water resources [12]. United States had implemented the effluent reuse up to potable water quality since 1976 at Water Factory 21, Orange County Water District, Southern California, where high quality water reclaimed from treated used water has been injected into ground water. Similarly, at Upper Occoquan Sewage Authority (UOSA), North Virginia, high quality reclaimed water is discharged into Occuquan Reservoir since 1978 [12]. For both countries, ultrafiltration and reverse osmosis membrane systems were used to treat the secondary effluent and UV was used as the disinfection tool.

UV provides a fast-acting, residual free method of coliform inactivation. UV has been shown to be a potential option for coliform inactivation in stringent wastewater reclamation applications [13]. Previous study by Darby *et al.* [14] had proven that UV disinfection satisfied the requirement for reclaimed wastewater in the State of California at reasonable doses. The advantages of UV treatment include providing microbial inactivation equivalent to chlorine while reducing the formation of known carcinogenic disinfection by-products and the formation of chronic effluent toxicity [15]. The hypothesis was that the addition of H_2O_2 to UV process will increase OH radical formation and could increase the inactivation rate of targeted microorganisms. It was also expected that the addition of H_2O_2 will reduce the UV dose and thus saving the energy consumption for actual application. UV became an attractive option because of UV effectiveness for inactivation of waterborne pathogens including cysts, oocysts of protozoan and intestinal parasites which are highly resistant to chlorination [16-17].

There are various types of bacteria and viruses in wastewater and it is impossible to analyse all types of these microorganisms. Total coliform, faecal coliform and *E.coli* which have been used as conventional indicators, are insufficient to evaluate the efficacy of the disinfection processes [18]. Studies to find other indicators that may provide a better indication of disinfection performance is important. In some other studies, coliphages were proposed to be used as surrogates to evaluate the efficiency of various water and wastewater treatment processes [20-21]. Evidence suggested that coliphages were more persistent in the environment and had been shown to be good indicators of human enteric viruses in polluted waters [21-22]. Coliphages are often proposed as indicators to identify the origin of faecal pollution [23]. Coliphages are easy to culture compared to actual human viruses and non-pathogenic because they are viruses of *E.coli*. They posses similar structure, morphology, origin, release and tolerance to environmental conditions compared to actual human viruses [19, 24].

In this study, *E.coli* and Qß, T4 and Lambda phage were used as targeted microorganisms. The objective of this study was to evaluate the inactivation characteristics during UV based disinfection processes on secondary effluent for reclaimed wastewater. The effect of secondary effluent constituents have also been investigated by measuring TOC and UV 254 during the inactivation processes.

2.0 MATERIAL AND METHODS

2.1 Selected Microorganisms

Four microorganisms were selected in this study namely *Escherichia coli* (*E.coli*), Qß phage, Lambda phage and T4 phage. Most of *E.coli* in water environment originates from faeces of human and animals, and their occurrence is, thus, very important in determining the origin of faecal pollution. Typically, *E.coli* account for approximately 11% of the coliforms in human faeces [25].

Qß phage has an icohedral capsid structure and genome consisting of positive-sense linear single-stranded RNA (ss-RNA). Qß phage poses similar size and morphology with enteric viruses and has been used as indicator for water quality assessment and routine monitoring [19, 23, 24]. In this study, Qß phage was selected to represent RNA group viruses in water.

Lambda phage, a virus that infects other bacteria with the ability to transfer genes among them, infects cells of the bacterium *E.coli*, where it can either exist as a quiescent prophage or undergo replication leading to lyses of the host cell and release of new phage particles. T4 phage has a non-segmented genome that contains a single molecule of linear double-stranded DNA (ds-DNA) [26,36]. T4 phage is from the family of *Caudovirales* and sub-family of *Myoviridae*. In nature, T4 phage is non-enveloped double-stranded DNA (ds-DNA). Lambda phage and T4 phage were selected to represent DNA-containing viruses [35].

2.2 Preparation of Selected Microorganisms

Qß phage (NBRC20012), Lambda phage (NBRC) and *E.coli* $K12F^+$ (A/λ) (NBRC13965) were obtained from National Institute of Technology and Evaluation Biological Resource Centre of Japan (NBRC). The Department of Urban and Environmental Engineering, Tokyo University provided T4 phage. Qß, T4 and lambda phage cultures were produced by adding the phages stock solution into exponentially growing *E.coli* $K12F^+$ (A/λ) and pure culture growing in the Difco™ LB Broth Lennox at 37ºC.

Suspended phages were collected by centrifugation (10000rpm, 20 min, 4ºC) and filtration through 0.45µm membrane filter (Milipore) to remove the cell lysate and to remove any other bacteria that may present. The stock phages suspensions were diluted 10-fold with phosphate-buffer solution (PBS, pH 7.2) to prepare the working phage suspension, essentially to avoid UV absorption by any proteins carried over from cell culture growth medium. The phage stock solutions were preserved at 4ºC for further experiment.

E.coli $K12F^+$ (A/λ) (NBRC13965) stock solutions were cultured in DifcoTM LB Broth Lennox at 37ºC shaking for 4 hours. The stock *E.coli* $K12F^+$ (A/λ) suspensions were diluted 10-fold with phosphate-buffer solution (PBS, pH 7.2) to prepare the working *E.coli* $K12F^+$ (A/λ) suspension. The stock solutions were also used as a host cell for plaque assay of all the phages.

2.3 Inactivation Experiment

In these experiments, the temperature of tested water was maintained at 20°C by circulating water into a water jacket outside the reactor using a water circulator. The low-pressure mercury UV lamp was manufactured by Iwasaki Electric Co., Ltd, Japan. Applied UV lamp was stabilised for 5 min before each experiment. In order to simulate the actual condition, a laboratory scale reactor (as shown in Figure 1) was used. Experimental conditions are shown in Table 1.

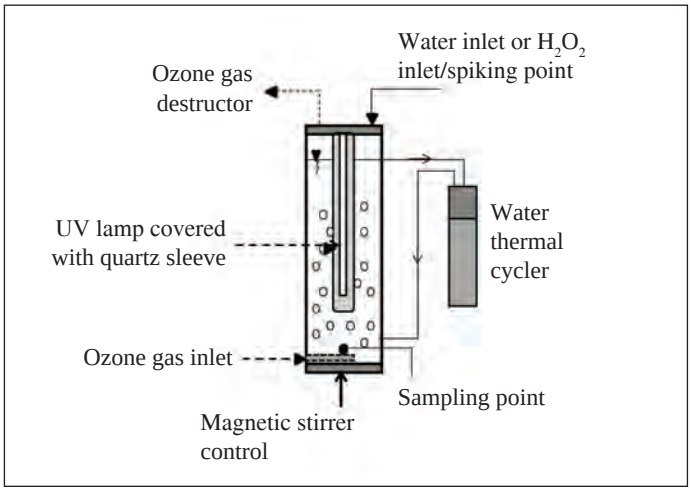

Figure 1: Schematic Diagram of Lab-Scale UV Reactor

Table 1: Experimental Condition

Microorganism	*E.coli*, Lambda , Qβ, T4			
Tested water	Secondary effluent			
Effective volume (L)	1.7			
UV wavelength (nm)	254			
UV intensity(mW/cm^2)				
Time contact (min)	0-10			
UV dose (mJ/cm^2)	0, 38.4, 76.8, 153.6, 230.4, 384			
Process	UV	UV/ H_2O_2	UV/ H_2O_2	UV/ H_2O_2
H_2O_2 concentration (mg/L) for *E.coli* and Qβ phage	0	2	4	6

2.4 UV Dose Measurements

UV is a physical disinfectant and the measurement of UV system performance occurred within the reactor. UV dose (mJ/cm^2 or mW-sec/cm^2) is expressed by multiplying the UV intensity (typically expressed in mW/cm^2) and contact time with the UV source (sec or min). UV intensity was determined from biodosimetry test.

2.5 The Inactivation Quantification by UV Based Experiment

The inactivation of targeted microorganisms were calculated by the basic model relationship log (N/No) = -Kt, where No is the coliphages or *E.coli* count at the initial time (time = zero), N is the coliphage count at contact time t, and K is the inactivation rate (slope function). The logarithm of the average inactivation coliphage or *E.coli* ratios were plotted against UV dose (UV intensity x contact time) and was computed as a linear or pseudo-first order kinetic reaction.

2.6 Detection Method

The indicator microorganisms were treated with UV and UV/ H_2O_2, and then 30 ml of tested water was collected from 0 to 10 minutes contact time. Contact time of 10 min was chosen based on a previous study [27]. It was shown that the most significant microbial reductions typically occur during the first 10-15 min of contact time. The samples were concentrated and purified with membrane filtration procedure [28]. In brief, 1M $MgCl_2.H_2O$ was added to final concentration of 0.05M and 1M HCl was added to final pH of 3.5. Membrane filtration method using cellulose acetate membrane filter with 0.45µm of pore size was adapted to recover the phages. After membrane filtration, phages recovered on the filter were eluted by 3% beef extract with pH 9.0.

The concentrated viruses were diluted 10-fold with Difco™ LB Broth Lennox and assayed in double agar layer with Difco™ Agar and plated out with *E.coli* K12F$^+$ (A/λ) (NBRC13965) as the host cells. All samples were prepared in duplicated petri dishes and incubated invertedly at 37˚C for 18 hours. The clear spot appeared in *E.coli* lawn represented dead cell of *E.coli* and known as plaque. The plaques were counted as Plaque Forming Unit per ml (PFU/ml).

E.coli was recovered using membrane filtration with 0.45µm of pore size after 10-fold dilution series [29]. The membrane filter containing filtered *E.coli* was laid on XM Nissui Agar to perform a blue colony after incubation at 37ºC when the *E.coli* enzyme reacted with the agar. The colonies were counted as Colony Forming Unit per ml (CFU/ml). All samples were prepared in duplicated dishes.

Each selected microorganism was spiked separately into the secondary effluent before treatment experiments to the final concentration of 10^6 PFU/mL.

2.7 TOC and UV_{254} Analysis

UV absorbance (UV_{254}) was measured by spectrometer (UV-16000, Shimadzu). The absorbance at 254nm (UV_{254}) was measured and indicates amount of unsaturated bonds in compounds in tested water. TOC concentration measured with Total organic carbon analyzer (TOC-5000A, Shimadzu). TOC is a measurement of organic compound in tested water.

3.0 RESULTS AND DISCUSSIONS

3.1 Inactivation Characteristics of Qβ, T4, Lambda phage and *E.coli* with UV Alone Process

The observed inactivation rates are shown in Figure 2. In comparison with coliphage Qβ under the same condition, coliphage T4 and Lambda demonstrated slower inactivation kinetics. *E.coli* was very sensitive to UV and displayed the fastest inactivation rates compared to the others.

The UV doses needed for 1-log to 4-logs inactivation for *E.coli*, coliphage Qβ, T4 and Lambda were calculated for comparison. The doses required for the 1-log and 4-logs inactivation, were calculated based on the regression analysis of each experiment. The doses of 46.9, 44.6, 32.1 and 27.8 mJ/cm^2 were needed to inactivate Lambda, T4, Qβ and *E.coli* respectively, by 1-log. The inactivation increased with UV doses. In order to achieve more than 4-logs inactivation, 128.2 mJ/cm^2 was needed for Qβ, whereas 178-188 mJ/cm^2 were required for T4 and Lambda.

Lambda phage was found to be the most resistant to UV treatment process in secondary effluent, followed by T4, Qβ and *E.coli*. Different UV doses were observed to achieve the same log inactivation of *E.coli*, Qβ, T4 and Lambda. Among all coliphage, Qβ was more susceptible to UV inactivation compared to T4 and Lambda.

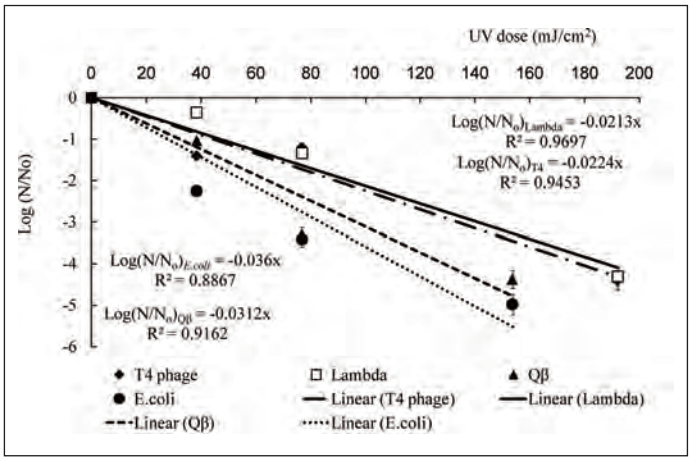

Figure 2: UV Inactivation of Targeted Microorganism (The error bars show maximum and minimum value for each duplicate dishes)

Previous study found that MS2, rotavirus, poliovirus and hepatitis A virus needed 64-93 mJ/cm^2, 50 mJ/cm^2, 23-29 mJ/cm^2 and 6-15 mJ/cm^2 respectively with UV process for natural waters to achieve 4-logs inactivation [30]. Based on the condition in this study, high dosage is required to achieve the same inactivation indicated the effect of the quality of tested water.

The significant differences in viral susceptibility to UV irradiation that of the cytosine content, or the complexity of the viral capsid and organisation of amino acids, carbohydrate and lipid composition of the protein capsid [17, 31]. Based on the characteristics of targeted microorganisms it could be suggested that protein coat (capsid) of T4 and Lambda may act as a partial shield against UV penetration to the genetic material. Capsid structure, as well as nucleic acid size, render ds-DNA virus less susceptible to UV inactivation [32].

UV disinfection could cause damage to the nucleic acid is well described in previous study [33]. But the knowledge of the ability to repair UV-induced effect or photo-reactivation to different microorganisms is still unclear. This ability could reduce the UV disinfection efficiency.

In order to ensure minimal biological risks, UV has the capability to establish as a primary disinfection for water reclamation facility. The susceptibility of selected microorganisms differed with the microorganism's characteristic. In this study, dsDNA bacteriophages T4 and Lambda demonstrated greater resistant compared with Qβ and *E.coli*. This finding is consistent with previous studies [29, 37].

3.2 Effect of H2O2 Addition on the Inactivation of Qβ phage and *E.coli* during UV Treatment

In order to reduce the energy consumption during treatment of high resistance virus and to control the photoreactivation of microorganisms, combination of UV with H_2O_2 is necessary and should be considered for actual wastewater reclamation facility.

The effects of H_2O_2 addition on the inactivation of Qβ and *E.coli* during UV treatment are illustrated in Figure 3 and Figure 4. These experiments were performed under three different initial H_2O_2 concentrations in order to compare the effects of H_2O_2 addition during UV treatment.

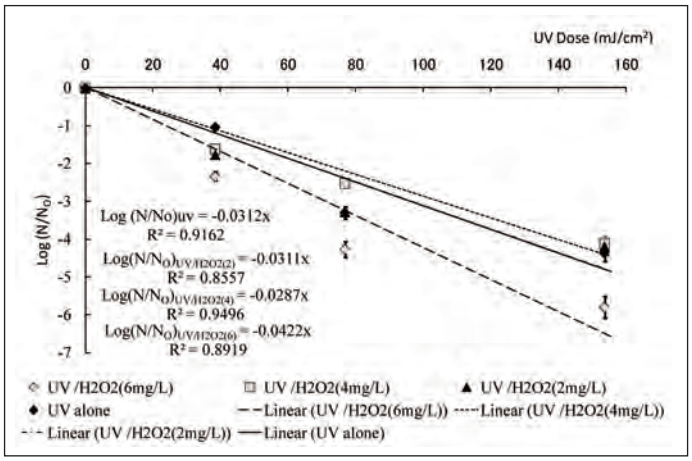

Figure 3: The Effect of UV/H_2O_2 Treatment Processes to Qβ Inactivation Rate (Error bars represent maximum and minimum value for duplicate experiments)

Figure 3 shows 3-logs inactivation occurs at 96 mJ/cm^2 for UV alone process. On the other hand, additional of 6 mg/L H_2O_2 reduced UV dosage to 71mJ/cm^2. By increasing the UV dosage to 160 mJ/cm^2, 5-logs inactivation could be achieved by UV alone process. UV combined with 2 mg/L H_2O_2 and 4 mg/L H_2O_2 did not significantly increased the inactivation rate. However, the combination with 6 mg/L of H_2O_2 yielded higher inactivation rate with lower UV dose at 118mJ/cm^2. It was calculated that combination of UV/H_2O_2 enable approximately 26% reduction in UV dosage to achieve the same log inactivation compared to UV process alone.

For the combined process, during coliphage Qβ inactivation in secondary effluent, the combination of UV and H_2O_2 promoted the production of hydroxyl radical and OH° radical formation increased the inactivation rate.

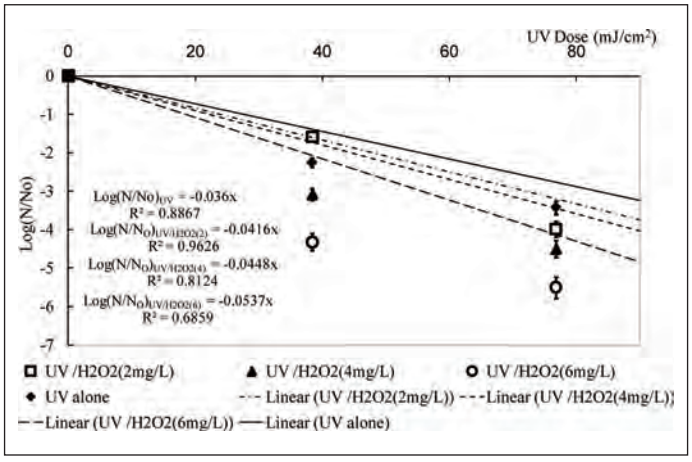

Figure 4: The Effect of UV/H_2O_2 Treatment Processes to E.coli Inactivation Rate (Error bars represent maximum and minimum value for duplicate experiments)

The combined processes of UV/H_2O_2 were tested for *E.coli*. The results showed that the addition of H_2O_2 significantly increased the inactivation of *E.coli* (Figure 4). The inactivation of *E.coli* gradually increased with additional of H_2O_2. For *E.coli*, 3-logs inactivation were achieved with 72, 67 and 55 mJ/cm^2

UV doses with addition of 2, 4 and 6 mg/L H_2O_2 respectively. The rates of inactivations of 5-logs were reached with 120, 112 and 93 mJ/cm^2 with 2, 4 and 6 mg/L H_2O_2, respectively. The combined processes were able to achieve approximately 32% reduction of UV dosage with 6 mg/L H_2O_2 compared to UV process alone.

The differences in disinfection efficiencies of UV and H_2O_2 could be explained by differences in mechanisms or susceptibility of indicator microorganisms to disinfectants. The main target of UV treatment are the nucleic acids, meanwhile the chemical H_2O_2 probably attacked the membrane walls, capsid or protein function for infectivity. The combination of UV/H_2O_2 produced OH˚ radical during the reaction to increase the inactivation rate of *E.coli* and Qβ. OH˚ radical is a strong oxidant and produced during advance oxidation processes such as UV/H_2O_2 and UV/O_3 treatment processes. Based on the results, the efficacy of combined UV/H_2O_2 depended on the ratio of UV dosage to H_2O_2 concentration. OH˚ radical is non-selective oxidant and react very fast in water. The combination of UV/H_2O_2 has been proposed as a measure to control photo-reactivation of microorganisms [38].

This study had shown that the secondary effluent treated with UV based processes had high potential to be used as reclaimed wastewater. Reduction of 1-log,3-logs,4-logs to 5-logs during UV based processes for *E.coli* and coliphages suggested that secondary effluent treated with UV based processes were suitable for restricted and non-restricted usage. Examples of potential usage include irrigation purposes and for receiving water being used for recreational activities with body contact [8, 9]. However, for more resistant viruses or for augmentation of drinking water supplies and dual reticulation in the building [10], higher quality is needed. The approach in producing NEWater by Singapore can then be considered, where microfiltration and reverse osmosis with UV disinfection were used to produce reclaimed wastewater for potable reuse [12]. This study was also found that the doses required for *E.coli* and coliphages were reasonable compared to USEPA requirement [39].

3.3 The Effect of Secondary Effluent Constituents

The significant effect of secondary constituents on coliphage Qβ and *E.coli* inactivation were examined. The required doses for 3 to 5-logs inactivation as determined from the experiment were correlated to the measured value of TOC and UV absorbance (UV254). The effect of dissolved organic compound (DOC) and UV absorbance are shown in Figures 5 – 8.

Most organic compounds absorbed UV energy, thus it can be expected that a correlation between DOC and inactivation would exist. DOC demonstrated strong correlations as seen in Figures 5 and 6 during Qβ phage and *E.coli* inactivation. The combined processes by addition of H_2O_2 during UV exposure produced OH° radical. OH° radical is highly reactive and can oxidize almost all contaminant in wastewater. However, organic compound in wastewater will undergo oxidative degradation and increased the competition of OH° radical consumption during the inactivation of microorganism.

UV absorbance reflects the quantity of UV energy absorbed by the medium (secondary effluent). Increased absorbencies mean that less UV energy is available for disinfection. In secondary effluent might contain many water matrixes showed strong correlation between UV_{254} and inactivation for indicator microorganisms as shown in Figures 7 and 8.

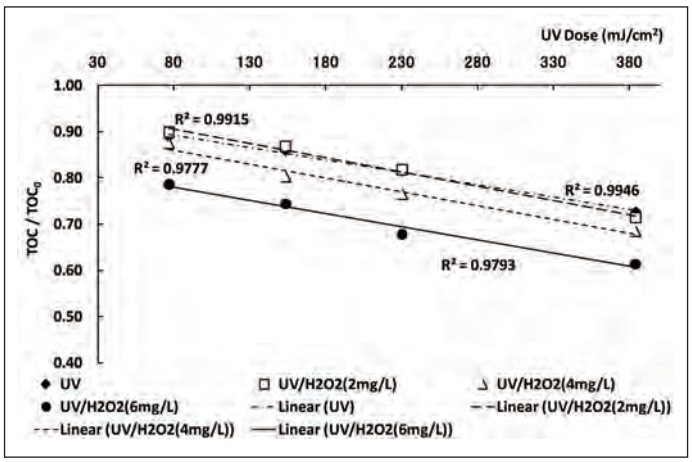

Figure 5: Correlation between UV Dose during Qβ Inactivation and DOC Reduction

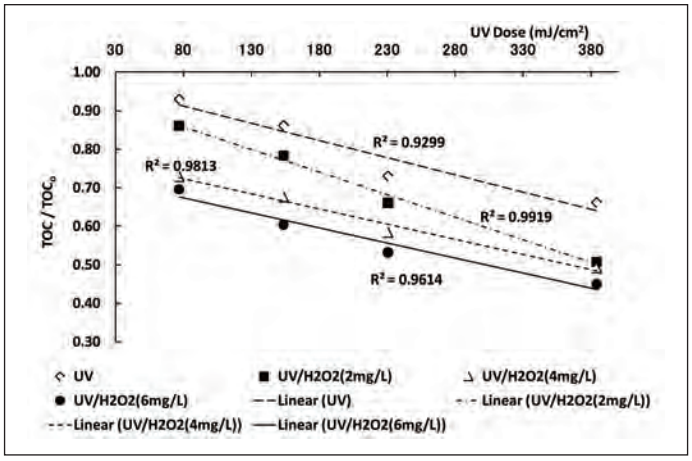

Figure 6: Correlation between UV Dose during E.coli Inactivation and DOC Reduction

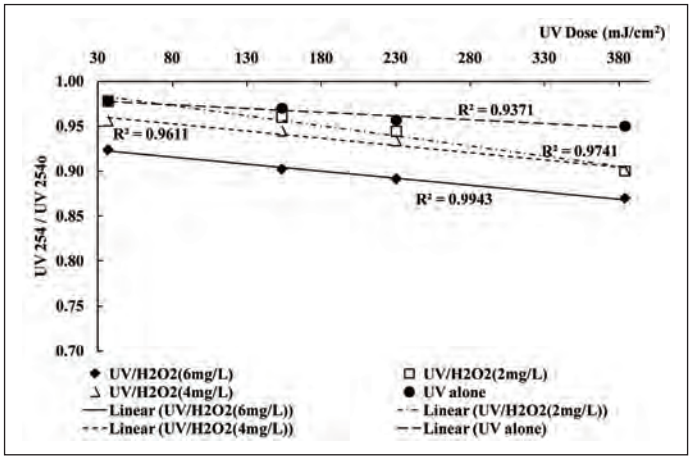

Figure 7: Correlation between UV dose during Qβ Inactivation and UV Absorbance

Other study has also found that constituents of secondary effluent will have significant impacts on reclaimed water quality [40]. Microfiltration and reversed osmosis membrane systems were used to treat secondary effluent from sewage treatment plant in Malaysia. The reclaimed water quality complied with all parameters set by WHO Guidelines for Drinking Water [41], except for Ammoniacal Nitrogen and total plate count [40]. The non-compliance of Ammoniacal Nitrogen was because the sewage treatment plant was not designed with nutrient removal

facilities. Thus, secondary effluent contained high Ammoniacal Nitrogen, which affects the reclaimed water quality. The total plate count did not comply because no disinfection facilities were provided. Therefore, the secondary effluent quality is expected to affect the reclaimed water quality in terms of chemical properties.

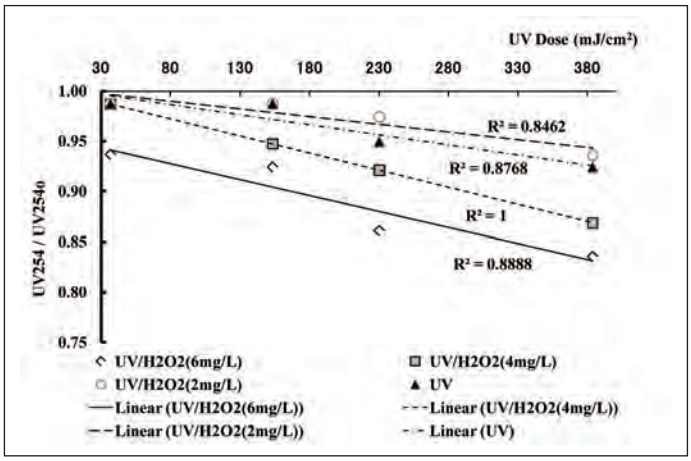

Figure 8: Correlation between UV Dose during E.coli Inactivation and UV Absorbance

4.0 CONCLUSION

This study emphasised on UV based processes for disinfection of selected microorganisms from secondary effluent. Secondary effluent was recognised as having a potential to be an alternative water resources as reclaimed wastewater. Nevertheless, the biological risks to end users should be considered. In order to reduce the biological risks of secondary effluent as reclaimed wastewater, proper disinfection is needed.

The results from this study provide information on the effectiveness of low-pressure UV treatment of *E.coli* and coliphage in secondary effluent using lab scale reactor. UV treatment process has efficiently inactivated *E.coli* and coliphage with effectiveness ranging from 1-log to 5-logs. The inactivation characteristics of each microorganism were differed due to their structure and characteristics. From this study, it can be concluded that Qβ phage from RNA group was more sensitive to UV process in comparison with T4 phage and Lambda phage from DNA group. More than 4-logs inactivation could be attained with 128.2 mJ/cm^2, 178 mJ/cm^2 and 188 mJ/cm^2 were required for Qβ, T4 and Lambda, respectively.

The combined processes of UV/H_2O_2 significantly increased the inactivation of *E.coli* and Qβ phage. This study indicated that the ratio of additional H_2O_2 played an important role for disinfection efficiency and could reduce the UV dosage.

DOC and UV absorbance strongly affected the UV based process. The competition between the organic compound in secondary effluent and inactivation of indicator microorganisms were observed for UV process and the combined processes.

Secondary effluent from the biological treatment after treating with UV based processes was found suitable for reclaimed wastewater. Disinfection processes using adequate UV dosage, will pose minimal biological risks and applicable for irrigations and many other purposes.

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MODELLING AND CONTROL OF AIRSHIP FOR LOW ALTITUDE SURVEILLANCES APPLICATION

(Date received: 08.03.12/Date accepted: 16.08.12)

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ABSTRACT

Aerial perspective provide great viewing window especially for surveillance and exploration activities. In responding to the need of green technology, airship is the best alternative for environmental friendly technology. In addition, airship is safer for low altitudes flying and able to maneuver at low speed in confined area. In order to drive the airship to the desired position, the airship's rudder must generate a yaw angle. Therefore, this paper presents the techniques to control the navigation path of an airship through the yawing state response. To provide good airship heading, optimal control and feedback control technique were proposed. The main goal is to produce an appropriate output signal by controlling the rudder deflection while reducing the excessive movements of the vehicles. The simulation demonstrate that the proposed controller effectively reduced the excessive movement for yaw rate and roll angle of the airship. It is shown that closed loop system has an error less than 1.6% with minimum overshoot of 2.04%. Comparatively, better results were obtained by introducing higher gain to the optimal controller thus contribute to low control response.

Keywords: *Airship, Lighter than air (LTA), LQR, Optimal control, State feedback*

1.0 INTRODUCTION

Aerial surveying technique offers an attractive economic approach for large scale monitoring with larger viewing window for a scene. By introducing the cameras and sensors to the aerial surveying activities, it will provide more potential information and eventually facilitate to faster and accurate decision making. Typically, airplanes, helicopters, UAVs and balloon were used in this activity. However, this geomatics technique required a stable, low vibration and slow moving platform to acquire good information. An alternative approach is by using an airship which enables efficient solution to better aerial visibility and lower vibration effect. Moreover, it will help to monitor the area behavior over time effectively thus responds to the needs of many activities such as marine planning, climate research and accessing risk areas.

In this paper, we proposed the lighter than air (LTA) technology to perform the aerial surveying using a non rigid airship. It is a very interesting concept which enables flying with low power consumption using gas with lower densities than air to provide aerodynamic and aerostatics lift. The airship was selected for the low altitude application due to the ability to hover in longer period over a particular area. It also capable to remain stationary therefore enables many promising data to be gathered. Several research studies has carried out on airship design [1-3], lifting method [4], dynamic modeling [5-7] and application [8]. In this work, we will consider helium as the lifting gas. This monatomic gas is the second lightest element which is very stables and nonflammables. Generally, the airships consist of 3 basic components: envelope/hull, gondola and fins as illustrated in Figure 1.

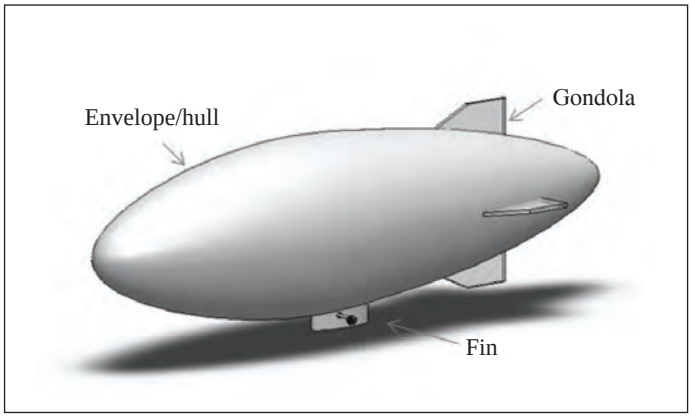

Figure 1: Airship component

The airship is able to fly slowly across a wide area for various reasons with capabilities to ascend, maneuver and descend by controlling its buoyancy. In order to obtain good information collection, the vehicles must able to follow the desired guidelines. The primary objective of this paper is to provide appropriate control signal to an airship based on the desired path. We will present two control schemes for controlling the left and right direction of the rudder deflection thus contribute to the vehicles

yawing movement. The proposed model movements were verified by introducing the control schemes. We will analyse the lateral system behavior of the airship based on the navigation path shown in Figure 2.

Figure 2: Closed loop navigation concept

The following Section II describes the dynamic model of the airship. We discuss the section by introducing assumptions, kinematics modeling and decoupled model for lateral and longitudinal. Section III present the control designs. The performances evaluation based on two controllers were presented in Section IV. Finally, Section V concludes the paper.

2.0 MATHEMATICAL MODELING

This section focuses on the formulation of integrated mathematical model of airship in state variable form. The physical dynamic effects were used to analyse the model behavior. We will briefly discuss the overall dynamics model comprises of decoupled longitudinal and lateral model [9,10].

2.1 Basic Assumptions

In order to investigate the model, it is convenient to define the references frames. There are two frames considered in this model: earth fixed references frame, F_e and body fixed references frame, F_b shown in Figure 3.

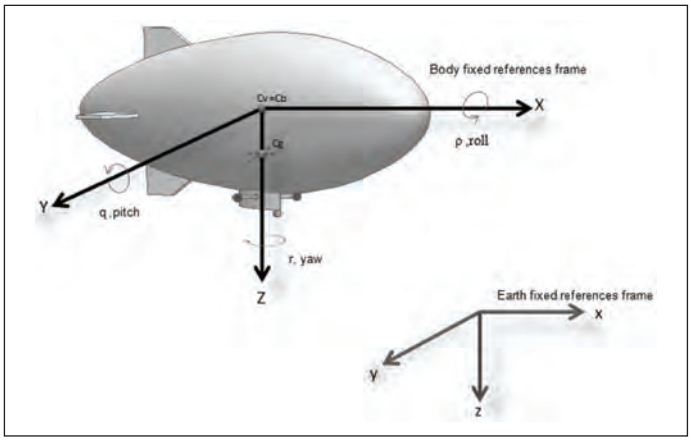

Figure 3: Two references frame. Earth References Frame (F_e) and Body Fixed Frame (F_b)

The Equation of motion (EOM) will be develop based on rigid body dynamic with several assumptions. In this case, the origin of F_b is coincides with center of volume, C_v in the plane of symmetry. For smaller size of airship, we can assume the center of gravity, C_g lies below where the location of C_g will not change significantly. Table 1 summarizes the notation used for the airship modeling.

Table 1: Notation for blimp model

Symbol	Description	Units
υ	Axial velocity perturbation	m/s
ν	Lateral velocity perturbation	m/s
w	Normal velocity perturbation	m/s
ρ	Roll rate	rad/s
q	Pitch rate	rad/s
R	Yaw rate	rad/s
Φ	Roll attitude	Rad
θ	Pitch attitude	Rad
ψ	Yaw attitude	Rad
δr	Rudder angle	Rad
δt	Thrust angle	rad

The decoupled lateral and longitudinal model have to be postulated to describe the airship motion in flight. The earth is assumed fix and flat during the dynamic analysis. Steady flight is considered to simplify the model where small perturbation may occur [10].

2.2 Dynamic Model

The dynamic model will be discuss in two parts: Kinematics and Dynamics. The force or moment due to aerodynamics, gravitational, buoyancy, and propulsion system were incorporated in the dynamic model, which is organised into continues state-space model. The following equation decisive the full nonlinear EOM written as

$$\dot{\eta} = J(\eta)v \tag{1}$$

$$M\dot{v} + fc(v)v + gb(\eta) + fd(v)v + fp = \tau \tag{2}$$

where $\eta \in R^3 \times S^3$ and $v \in R^6$, M is the system inertia matrix, *fc(v)* is the coriolis-centripetal matrix, *fd(v)* is the damping matrix, *gb(η)* vector of gravitational/buoyancy forces and moments, *fp* propulsion notation and τ is the vector of control inputs.

Kinematics: By incorporating (1) with rotation and transformation matrix. The overall 6 DOF

Equation is given by

$$\dot{\eta} = \begin{bmatrix} R^{Ob} & 0_{3\times3} \\ 0_{3\times3} & T_\Theta \end{bmatrix} v \tag{3}$$

where $v = [u, v, w, p, q, r]^\intercal$ and $\eta = [x, y, z, \phi, \theta, \psi]^\intercal$.
The model matrix , R^{Ob} denoted the rotation matrix given by

$$R^{Ob}(\Theta) = \begin{bmatrix} c\psi c\theta & s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi - c\psi s\theta c\phi \\ -s\psi c\theta & c\psi c\phi - s\psi s\theta s\phi & c\psi s\phi + s\psi s\theta c\phi \\ s\theta & -c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{4}$$

where sϕ=sin(ϕ) and cϕ=cos(ϕ) valid for $-\pi/2<\theta<\pi/2$. While T_Θ is the transformation matrix simplifies to

$$T_\Theta(\Theta)=\begin{bmatrix}1 & s\phi t\theta & c\phi t\theta\\ 0 & c\phi & c\psi s\phi + s\psi s\theta c\phi\\ 0 & \frac{s\phi}{c\theta} & \frac{c\phi}{c\theta}\end{bmatrix} \quad (5)$$

Dynamics: In the decoupled model, the horizontal axis and vertical axis behavior can be represent as lateral and longitudinal model. In lateral case, the state vector considered for the dynamic characteristics involve the state $x^T=[v\ p\ r\ ø]$ and rudder deflection as the control input denoted as $u^T=[\delta_r\ ]$. The model can be defined by the following state space representation

$$a=\begin{bmatrix}Y_v & m_zW_e & -m_xU_e & (mg-B)cos\theta_e\\ 0 & L_p-ma_zW_e & ma_zU_e & -(mga_z-Bb_z)cos\theta_e\\ 0 & ma_xW_e & N_r-Ma_xU_e & (mga_x-Bb_z)cos\theta_e\\ 0 & 1 & 0 & 0\end{bmatrix} \quad (6)$$

$$b=\begin{bmatrix}Y\\ 0\\ \Gamma\\ 0\end{bmatrix} \quad (7)$$

$$m=\begin{bmatrix}m_y & -ma_z & ma_x & 0\\ -ma_z & J_x & J_{xz} & 0\\ ma_x & -J_{xz} & J_z & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (8)$$

where $A=m/a$ is the system matrix, $B=m/b$ is the control matrix, m is the added mass matrix, J is the moment of inertia, U_e,W_e are the linear velocity component, B is the buoyancy force, b_x,b_z are the centre of volume, mg is the gravitational force, $Y,\Gamma,M_\delta,Z_\delta$ are the geometric and aerodynamic symmetry, respectively. In longitudinal model, the state vector considered for the dynamic characteristics $x^T=[u\ w\ q\ \theta]$ and $u^T=[\delta_e\ \delta_t\ ]$

$$a=\begin{bmatrix}X_u & 0 & -m_zW_e & -(mg-B)cos\theta_e\\ 0 & Z_w & m_xU_e & -(mg-Bb_z)sin\theta_e\\ 0 & 0 & M_q-ma_xU_e-ma_zW_e & -(mga_x+Bb_z)cos\theta_e+(mga_z+Bb_x)sin\theta_e\\ 0 & 0 & 1 & 0\end{bmatrix} \quad (9)$$

$$b=\begin{bmatrix}0 & X_t\\ Z_\delta & 0\\ M_\delta & 0\\ 0 & 0\end{bmatrix} \quad (10)$$

$$m=\begin{bmatrix}m_x & 0 & ma_z & 0\\ 0 & m_z & -ma_x & 0\\ ma_z & -ma_x & J_y & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (11)$$

where X_u, Z_w, M_q are the dimensional derivative symbol and derivative X_t is the trust coefficient. In order to determine the airship analysis, simulation were performed using the following features. The details are described as follows: The airship shape is consider ellipsoid with length of 1.6764 m and maximum diameter of 0.385 m. The detail of the model can found in [9].

3.0 AIRSHIP CONTROL

In order to perform the aerial surveillances, the airship should have the ability to control the amount of rudder angles being exerted while following the desired trajectory. The control objective is to maintain the minimum control signal which takes the plant to desired states. It is practical to used decouple model of blimp while assuming small perturbation about the trimmed equilibrium [10]. In lateral control design, only the rudder will contribute to yawing with minimum roll taking place. The rudder deflection ability was set between +30 to -30 degree. In this case positive angles contribute to left deflection. The output affected by this model will be v, p, r and ϕ. Figure 5 shows the block diagram of the proposed system.

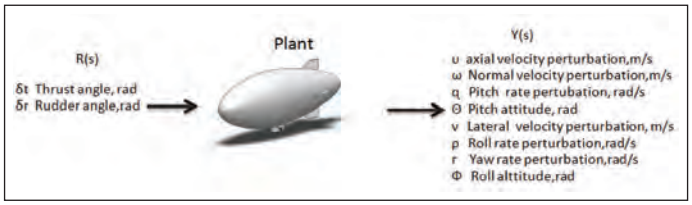

Figure 4: Lateral dynamic open loop response

An optimal control and state feedback scheme were implemented on the airship model as discusses previously. In order to study the model behavior, three initial simulations were done for designing the controller. The system model must be controllable, otherwise the control input will not affect all the states variables.

Property 1: In order to provide ability to place the pole location based our needs, is important to make sure that we obtain full rank value. The controllability matrix, c is given by $C = [B\ AB\ A^2B\ \ldots\ldots\ A^{(n-1)}B]$, where B and A are representative of the EOM using state space method. Proof: Using equation (6)-(11) the forces ad moments equation based on the design proposed were written as

Lateral model

$$A=\begin{pmatrix}0.0191 & 0.0175 & -5.6166 & 10.0366\\ 0.3412 & 0.0005 & -1.0347 & 4.2577\\ -0.0006 & 0.0000 & 0.1831 & -0.0075\\ 0 & 1 & 0 & 0\end{pmatrix}$$

$$B=\begin{pmatrix}0.5131\\ 8.9846\\ 5.2080\\ 0\end{pmatrix}$$

Longitudinal model

$$A=\begin{pmatrix}-0.1946 & 0.0000 & -0.0114 & -9.4097\\ -0.0009 & -0.0067 & 5.4433 & 0.1646\\ 0.3150 & 0.0003 & -0.0376 & -0.6386\\ 0 & 0 & 1 & 0\end{pmatrix}$$

$$B=\begin{pmatrix}-1.2214 & 0.0189\\ 0.9915 & 0\\ 7.1150 & 0.0101\\ 0 & 0\end{pmatrix}$$

Clearly, the matrix $\mathbb{C}$ has full rank. The system is controllable since rank of $\mathbb{C}$ equal to system size of 4.

Property 2: Necessary for us to investigate what happing inside the system thus, observability $\mathbb{O}$ matrix, must meet the requirement given by following equation

$$\mathbb{O} = \begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{pmatrix}$$

where *C* and *A* are representative of the EOM using state space method. *Proof:* Due to same size given, it proved that the system is observable due to full rank.

Property 3: Stability of the plant is based on eigenvalues of matrix A. For the lateral model, it contribute to these poles 2.3911, -1.2571, -1.1125 and 0.1813 and longitudinal provided 0.5746 + 1.3804i, 0.5746 - 1.3804, -1.3814, -0.0067. Since there are 2 RHP therefore the system is unstable. Figures 5 and 6 shows the simulation when an input is applied to the uncontrolled system. The decoupled models are inherently unstable, when an input is applied to the open loop system, it causes all states rise unbounded as the airship travel.

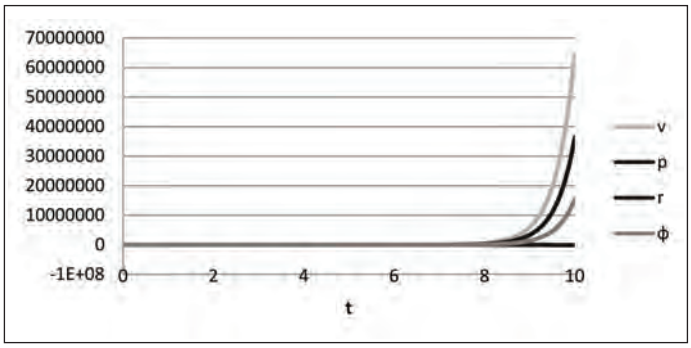

Figure 5: Lateral dynamic open loop response

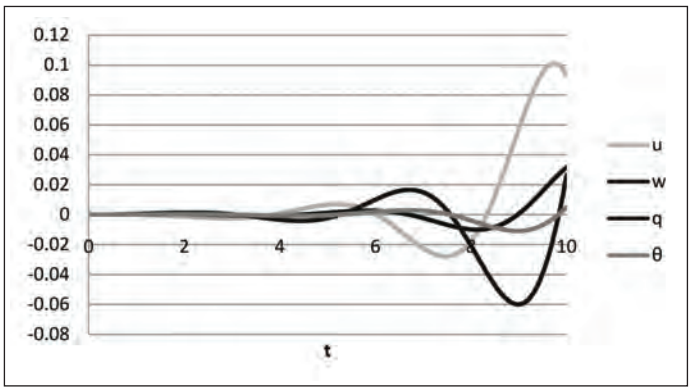

Figure 6: Longitudinal dynamic open loop response

3.1 Optimal Controller: Linear Quadratic Regulator (LQR)

The LQR method is a powerful method for designing controller for complex systems with stringent performances. This design seeks for optimal controller values that minimises control input, u(t) by iterative until the desired behavior of control is achieved. The optimal value was obtained by manipulating two matrices, *Q* and *R* that weight the state vector. The performances criterion is given by

$$J(x,u) = \frac{1}{2}x^T(t_f)sx(t_f) + \int_{t_0}^{t_f}[x^T(t)Qx(t) + u^T(t)Ru(t)]dt$$

where *S* and *Q* are symmetric, positive-semidefinite weighting matrices; and R is a symmetirc, positive-definite weighting matrix. In this paper, the selection of Q and R metric were done based on Bryson rules. Based on the model (6) and (8), the LQR gain were given by, K = [0.5039 3.4956 - 4.1256 8.3520].

3.2 Pole Placement by State Feedback Controller

In this control scheme, the designer able relocates all the closed loop poles of the system to desired locations. The selections of values of the state feedback vector effect the shape of the plant output. In order to meet the design specification, the best value of poles and zeros becomes a matter of trial and error. The poles of the system have to be placed carefully due to costs that are associated with shifting pole locations. For best results, several simulation trials using MATLAB have to be performed to achieve desired response while not straining the control input, *u(t)*. According to a control law as follows

$$u(t) = K[x_d(t) - x(t)]$$

where *x(t)* is the state-vector of airship, $x_d(t)$ is the desired state-vector. The controller aims to achieve desired rudder deflection if the airship model in the steady state. The input vector, *u(t)* were used as input to model. The final results of tuning for the optimal pole location to achieve desired objectives are P = [-1, -2, -2.89, -3]. These values contribute to controller gain K = [0.4574, 3.2026, -3.8241 and 7.5774].

4.0 RESULTS

In this section, we present two continuous-time based controllers: The optimal controller (LQR) and state feedback controller using pole placement method with reference input. The design of controller is based on the lateral modeling for driving the airship to monitoring an area. The navigation path was given based on the scene to be view. In this work, the navigation path was set as shown in Figure 7. For desired input, the peak value were 0.0172 rad which contribute to 1 degree, with each pulse stay for 8s (enough time to converge to steady state) and assuming time taken to monitor small area is 80 second.

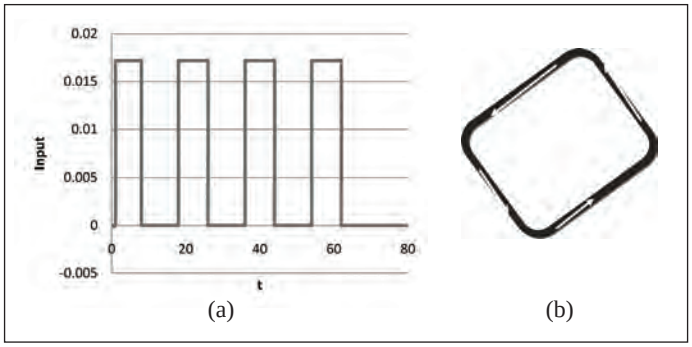

Figure 7: Desired input for rudder deflection (a) signal generated based on anticlockwise looping (b) proposed navigation

4.1 Linear Quadratic Regulator (LQR)

Referring to Section III, we have implemented the proposed control scheme on our model. The summarises result obtained from the simulation are given in Table III. The input unit was described in degree to represent the real behavior of the blimp. Figure 8 illustrated the overall lateral states behavior when 1

degree of deflection is applied. The simulations were done using Matlab/Simulink software. The control *Q* and *R* matrix follows the Bryson rules by introducing gain value of 1 in the selected matrix area to show that the model adaptability. The result shows, that the control unit, *u(t)* value are able to stabilise the airship within approximately -0.016 to 0.016, it is rather small thus minimises the controlling cost.

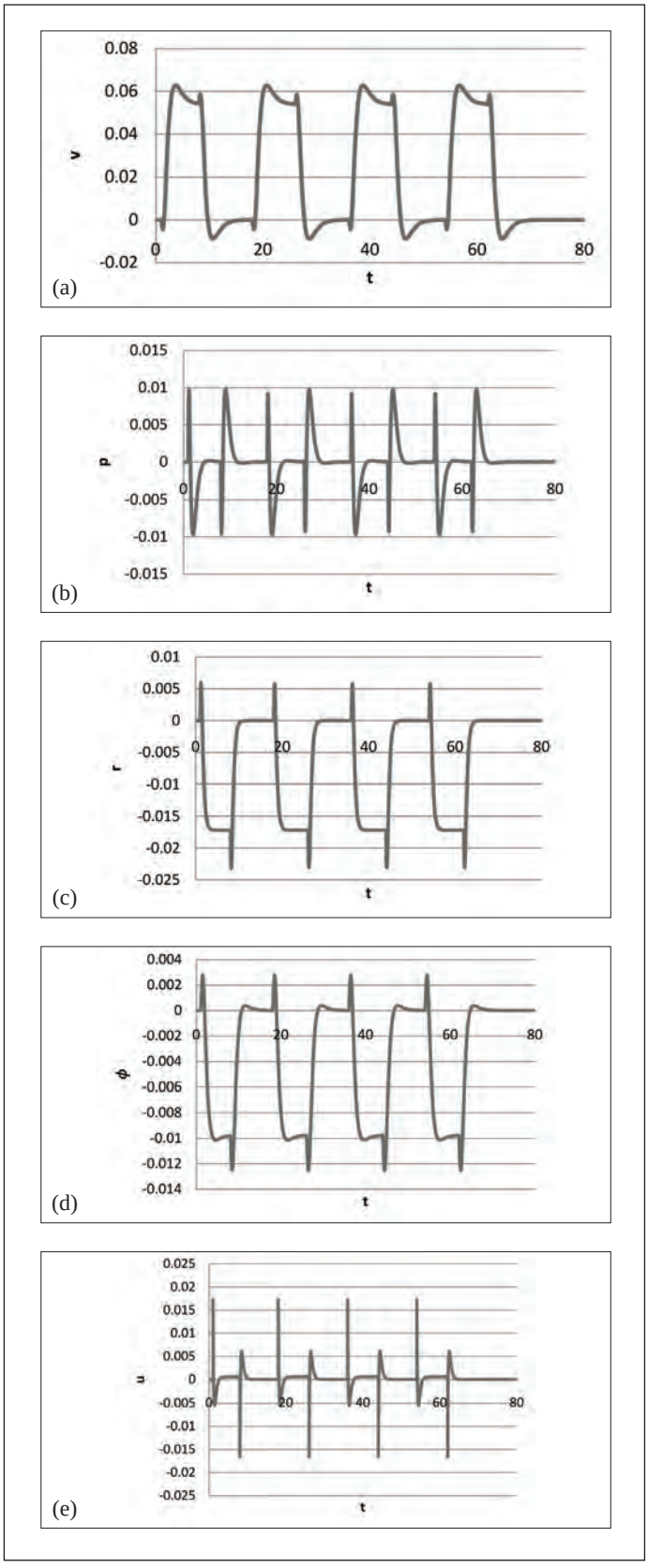

Figure 8: Output for rudder deflection for overall states (a) velocity (b) roll rate (c) yaw rate (d) roll altitude (e) control unit

Using desired input value 1 deg (0.0172 rad), the airship should be able to yaw to the left. Note that positive angles contribute to left deflection on the yawing angles. Figure 9 show that the positive angles contribute to negative angles reflecting the negative values as the left deflection. This proves the model behavior follow the design requirement. In order to observe the behavior of vehicles navigation, a range of input were given between 0 and 30 degree. The opposite values give similar amplitude value but with different polarity.

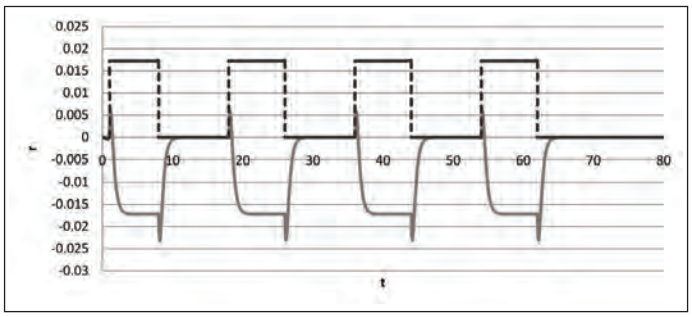

Figure 9: Output versus actual, r

In this analysis, a pulse was injected for 8 second for 4 times to sample the behavior of closed loop navigation. If longer pulse were given the same shape of response will be display but with different time range. However if small time pulse were given the system will not have enough time to stables the previous cycles signal and continuing to overcome new goal.

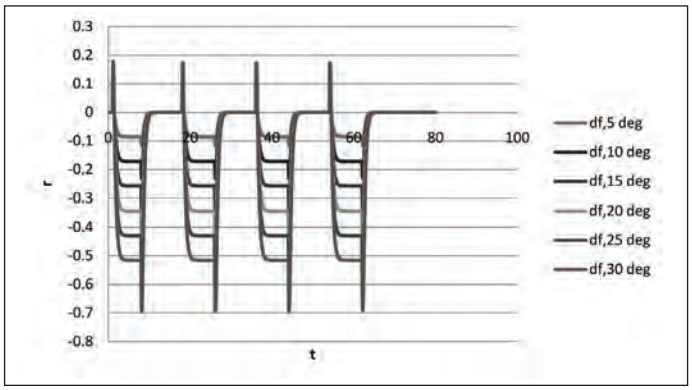

Figure 10: Actual output of rudder deflection

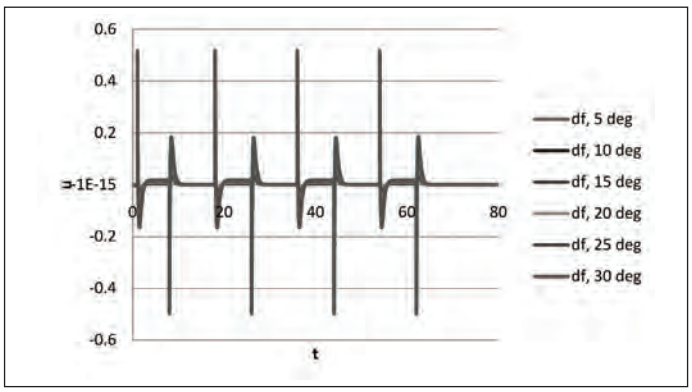

Figure 11: Control signal, u(t) of LQR

Rudder angles simulation

The dynamic is input with angle of 0 to 30 degree using input as shown in Figure 7. The smaller time values were used as samples to analyses the system behavior. The responses of the states were shown in Figure 10. Note that this based on 180 degree left and

right movement. The system responses for yaw rate for each deflection concluded in Table 2 and 3. All results were describes in degree unit.

Table 2: Result of the simulations

	Time, s	5 deg	10 deg	15 deg	20 deg	25 deg	30 deg
Rise time, Tr	2.4151	-4.31	-8.63	-12.95	-17.27	-21.58	-25.89
Peak time, Tp	1.1458	1.71	3.41	5.12	6.83	8.54	10.24
OS%	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Settling time, Ts	-4.9617	-4.92	-9.84	-14.77	-19.69	-24.61	-29.53
min point	8.1732	-6.65	-13.29	-19.93	-26.57	-33.22	-39.86

Table 3: Result of the simulations

Desired	| Actual |	| e |	| e |%
5	4.9224	0.0776	1.5525
10	9.8447	0.1553	1.5525
15	14.7671	0.2329	1.5525
20	19.6895	0.3105	1.5525
25	24.6119	0.3881	1.5525
30	29.5342	0.4658	1.5525

Table 2 describes the output responses characteristic for each deflection. The results shows that each rudder deflection follows the target value quickly without overshoot. The proposed LQR output gives good results however each transition suffer from inverse movement in short time. This reflect to the real effect of the vehicle that may affected by sliding issues. In Table 3, the desired and the actual value are listed for vehicles yawing. It can be concluded that the error contribute approximately 1.6 % with control unit amplitude of max deg of ±0.516 and min deg of ±0.086. The results confirm the design able to accomplish the control objective.

4.2 Pole Placement by State Feedback Controller

Next, by repeating the same model analysis with statefedback controller. Results for this scheme are shown in Figure 12. The summarises result were presented in Table 6 and 7. In this control technique, we placed the desired poles on the left half plane of s-plane for stability. The values of K are obtained by introducing several poles during the simulation based on the trial and error concept.

By introducing 1 deg (0.0172 rad) of input to the model, all states are able converge to target response. Figure 12 shows, the positive angles deflection of rudder contribute to left deflection on the yawing angles. The system responses for yaw rate for each deflection were concluded in Table 4 and 5.

The results shows that the system able to achieve desired output although with overshoot. From the observation the similar output shape response obtained from previous scheme. In Table 3, the desired and the actual value are listed for vehicles yawing. It can be concluded that the error contribute approximately 0.7 % smaller than LQR result.

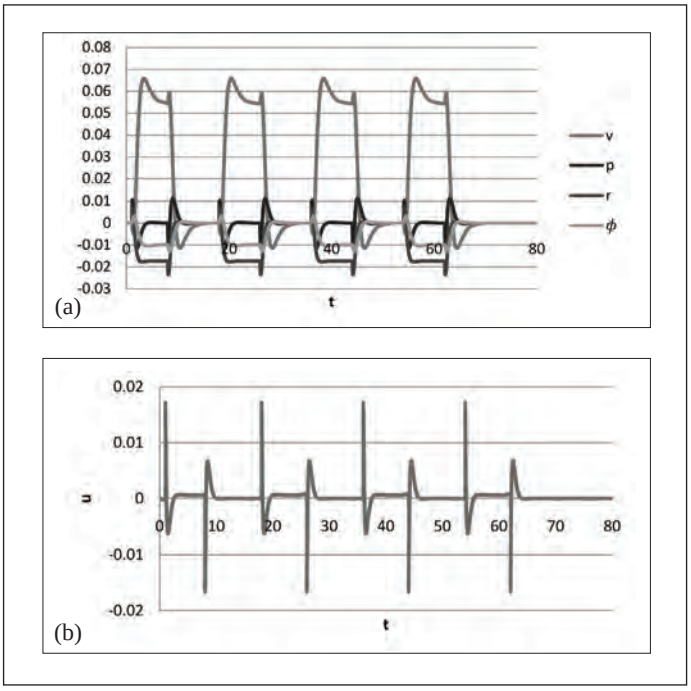

Figure 12: State feedback system design (a) States response output using state feedback (b) Control signal, u(t)

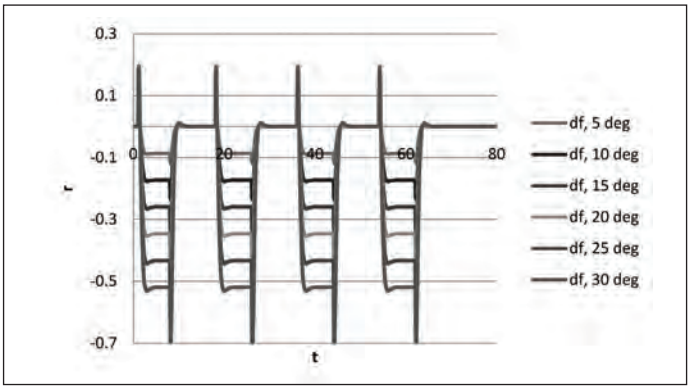

Figure 13: Actual output of rudder deflection

Table 4: Result of the simulations

	Time, s	5 deg	10 deg	15 deg	20 deg	25 deg	30 deg
Tr	2.438646	-4.851	-9.702	-14.552	-19.403	-24.254	-29.105
Tp	1.156074	1.864	3.727	5.591	7.454	9.318	11.181
OS	2.837457	-0.101	-0.202	-0.304	-0.404	-0.506	-0.607
Ts	6.7601	-4.961	-9.922	-14.884	-19.845	-24.806	-29.766
Min point	8.128674	-6.742	-13.484	-20.226	-26.967	-33.710	-40.451

Table 5: Result of the simulations

Desired	| Actual |	| e |	| e |%
5	4.9611	0.0389	0.7776
10	9.9222	0.0778	0.7776
15	14.8834	0.1166	0.7776
20	19.8445	0.1555	0.7776
25	24.8056	0.1944	0.7776
30	29.7667	0.2333	0.7776

The results of both controllers were compare to validate the achievement of each parameter. The responses on each states difference were illustrated in Figure 14 and 15. We see that small different occur for each state. The LQR and state feedback have similar response shape. LQR able to minimize the control cost without overshoot and complete the cycle quickly. However recorded higher error than the state feedback controller. Even though the state feedback gives better result in term of error, rise time and settling time. The system comes with 2% of overshoot for each desired deflection.

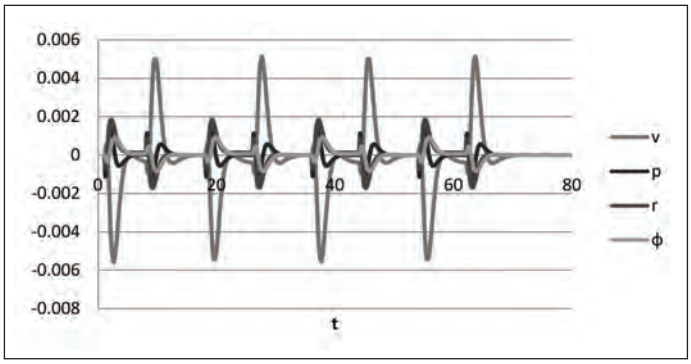

Figure 14: Output response difference between two controller

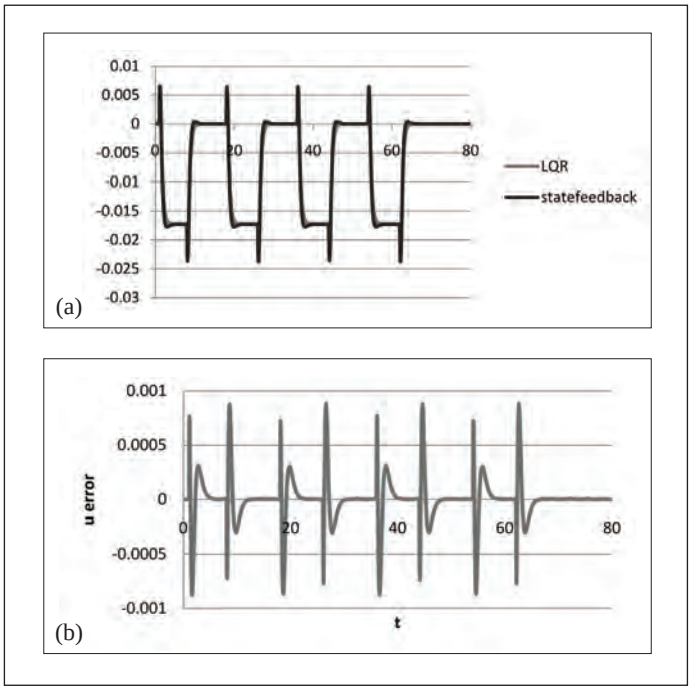

Figure 15: Comparisons (a) Comparison of yaw rate (b) Error difference between two controllers

For |e|, LQR has higher value of 1.6% than state feedback 0.78 %. In this design the LQR, the matrix value was based on Bryson rule without increasing the gain. In order to achieve better result higher value of Q matrix can be introduce to improve the system behavior. The details of each parameter are shown in Table VI and VII.

Throughout the analysis, both controllers are able to achieves the control objectives. Although LQR method contributes to higher error compare to the state feedback, this method is more robust. Therefore only a small different occur between these two controller with very small error for yawing rate thus contribute to good navigation results.

Table 6: Controller comparison

(SS-LQR)	Time, s	5 deg	10 deg	15 deg	20 deg	25 deg	30 deg
Tr	0.023546	-0.54	-1.07	-1.61	-2.14	-2.67	-3.20
Tp	0.010274	0.16	0.31	0.47	0.62	0.78	0.93
OS	2.837457	-0.10	-0.20	-0.30	-0.40	-0.51	-0.61
Ts	1.7984	-0.04	-0.08	-0.11	-0.15	-0.19	-0.23
Min point	-0.04453	-0.10	-0.20	-0.30	-0.40	-0.49	-0.60

Table 7: Controller comparison

Desired	| Actual |	| e |	| e |%
5	0.0387	0.0387	0.7749
10	0.0775	0.0775	0.7749
15	0.1163	0.1163	0.7749
20	0.155	0.155	0.7749
25	0.1937	0.1937	0.7749
30	0.2325	0.2325	0.7749

5.0 CONCLUSION

In this paper, an airship model that will be used in navigation is analysed. The small airship modeling is based on our design requirement. The configuration of an airship will affect the model controllability and the control law response. Two lateral lateral controllers we proposed in Section III enable the rudder defection control that define the yawing rate and roll of the airship. Although, our model was unstable, the proposed controllers were able to help the airship achieve navigation path. However, these methods need to be tune several times in order to obtain the best states response. We have proven that both controller, were sufficient for the airship to reach the goal. For more robust application, the LQR gives more effectives control strategies thus offer precise control for airship heading with less tuning.

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