A mathematical model of traffic noise at a signalized intersection

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Abstract

Paoprayoon, S., Wongwises, P. and Narupiti, S.
A mathematical model of traffic noise at a signalized intersection
Songklanakarin J. Sci. Technol., 2005, 27(3) : 535-548

This research aims at modeling interrupted flow traffic noise at a signalized intersection. The models are mathematically derived by applying the inverse square law of sound pressure incorporating with theories of traffic flow at an intersection. The traffic flow theories utilized for developing the model consist of characteristics of individual vehicle motion at intersection, shock wave model, and queuing analysis. The model formulation is divided into two different approaches and takes into account of all regimes of vehicle movement while traversing an intersection (i.e. idling, decelerating, accelerating, and cruising conditions). The first approach assumes a constant acceleration/deceleration rate for each type of vehicle. Another applies inconstant acceleration/deceleration which comes from speed-distance relationship. The final models are expressed in L_{Aeq} (1 hr).

Eventually, the developed models are validated by collecting equivalent continuous noise level in 1 min as well as traffic parameters (i.e. red time, number of vehicle in the queue, queue length, time of queue dissipation, and final cruise speed) from fifteen vehicle platoons. The noise levels predicted from the developed models are compared with the measured ones. The results show that the inconstant acceleration

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Songklanakarin J. Sci. Technol.   Mathematical model of traffic noise

Vol.27 No.3 May - Jun. 2005   **536**   Paoprayoon, S., *et al.*

model gives the predicted levels closer to the measured ones than constant acceleration model. The error of inconstant acceleration model ranges from 0.1-3.9 dB(A) with the average value of 2 dB(A) overestimated and that of constant acceleration model ranges from 1.8-6.5 dB(A) with the average value of 3 dB(A) underestimated. It might be concluded that movement characteristic of vehicle is an important factor that apparently affects the accuracy of traffic noise prediction at an intersection.

Key words : acceleration, interrupted flow, noise emission level, traffic noise,
signalized intersection

บทคัดย่อ

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แบบจำลองทางคณิตศาสตร์ของเสียงจากการจราจรที่บริเวณสี่แยกสัญญาณไฟ

ว. สงขลานครินทร์ วทท. 2548 27(3) : 535-548

งานวิจัยนี้เป็นการพัฒนาแบบจำลองทางคณิตศาสตร์และวิธีการในการพยากรณ์เสียงจากการจราจรที่บริเวณ สี่แยกสัญญาณไฟ โดยแบบจำลองถูกพัฒนามาจากทฤษฎีกำลังสองผกผันของความดันเสียงประกอบกับทฤษฎี พฤติกรรมการไหลของจราจรที่บริเวณสี่แยก ซึ่งได้แก่ พฤติกรรมการเคลื่อนที่ของรถยนต์ขณะเร่งออกจากสี่แยกและ การเคลื่อนที่ขณะชะลอความเร็วเข้าสู่สี่แยก การวิเคราะห์อัตราช็อคเวฟและการวิเคราะห์ความยาวแถวคอยของรถที่ ติดไฟแดง แบบจำลองแบ่งออกเป็น 2 รูปแบบตามลักษณะพฤติกรรมการเคลื่อนที่บริเวณสี่แยก ได้แก่ แบบจำลอง ที่ใช้พฤติกรรมการเร่ง/ชะลอแบบไม่คงที่ซึ่งอธิบายการเคลื่อนตัวบริเวณแยกด้วยกราฟความเร็วและระยะทาง และ แบบจำลองที่ใช้อัตราเร่ง/ชะลอแบบคงที่ซึ่งอธิบายการเคลื่อนตัวบริเวณแยกด้วยอัตราเร่ง/ชะลอแบบคงที่ ดัชนีค่า ระดับเสียงที่ใช้ในแบบจำลองที่สร้างขึ้นคือ ค่าระดับเสียงเฉลี่ย 1 ชั่วโมง (L_{Aeq} 1hr)

แบบจำลองทั้งสองรูปแบบที่พัฒนาขึ้นถูกประเมินในด้านความแม่นยำในการพยากรณ์โดยการเก็บข้อมูลค่า ระดับเสียงเฉลี่ย 1 นาทีของขบวนรถ 15 ขบวนพร้อมด้วยค่าพารามิเตอร์ด้านการจราจร ซึ่งได้แก่ ระยะเวลาไฟแดง จำนวนรถในขบวน ความยาวแถวคอย ระยะเวลาการสลายตัวของแถวคอยและความเร็วคงที่สุดท้ายของขบวนรถ ผลการพยากรณ์ระบุว่าแบบจำลองที่ใช้พฤติกรรมการเร่ง/ชะลอแบบไม่คงที่ให้ค่าที่ใกล้เคียงกับค่าที่วัดจริงมากกว่า แบบจำลองที่ใช้อัตราเร่ง/ชะลอแบบคงที่ โดยแบบจำลองแบบแรกให้ค่าความคลาดเคลื่อนในช่วง 0.1-3.9 dB(A) และ มีค่าเฉลี่ยประมาณ 2 dB(A) สูงกว่าค่าที่วัดได้ ส่วนอีกแบบจำลองหนึ่งให้ค่าความคลาดเคลื่อนในช่วง 1.8-6.5 dB(A) และมีค่าเฉลี่ยประมาณ 3 dB(A) ต่ำกว่าค่าที่ได้จากการวัด ซึ่งแสดงให้เห็นว่าลักษณะการเคลื่อนที่ของการจราจรเป็น ปัจจัยสำคัญที่มีผลอย่างมากต่อความแม่นยำของการทำนายเสียงจากการจราจรบริเวณสี่แยก

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Traffic characteristics and behaviors at a signalized intersection, which are affected by traffic control devices, generate traffic noise levels differently from uninterrupted traffic flow condition. This is because of the vehicular speed varying with the distance to/from the intersection. Furthermore, the different signal timings produce the complicated characteristics of traffic streams and also traffic noise levels. Therefore, the prediction of interrupted flow traffic noise level is still a difficult and tedious task for analysts. A variety of researches on traffic noise around the world focus on the uninterrupted condition that is much less perplexing. However, only few studies attempt to formulate the reliable methods for traffic noise prediction at an intersection. Some of those

methods just approximate the traffic noise values by constructing the relationship of traffic noise with the other relevant parameters using multiple regression analysis whereas the others formulate much more complicated models based on physics theories. The problems occurring are that the traffic noise levels predicted using the approximation method are not accurate enough. The models which are constructed with complicated theories cannot be conveniently applied to the real situation (Steele, 2001). As a result, this study tries to formulate a new interrupted flow traffic noise model which is more theoretically acceptable and is conveniently applicable for real traffic condition. A few traffic flow theories as well as characteristics of individual vehicles traversing an intersection are used to formulate the model. In addition, the model is also tested with the noise data collected from several vehicle platoons to determine its validity and accuracy. It is anticipated that traffic noise prediction model developed from this study will result in the more effective measure for environmental noise assessment at signalized intersections.

Methodology

This research is divided into two main sections. The first is the development of interrupted flow traffic noise models at a signalized intersection which is explained along with the explanation and application of traffic flow theories. Another section is the validation of the constructed models which explains the collection methods of traffic noise and traffic flow parameters.

1. Development of Interrupted Flow Traffic Noise Models

A fundamental noise theory used for constructing the models is inverse square law of sound pressure of a moving vehicle as illustrated in Figure 1. According to the inverse square law theory, it is stated that the square of sound pressure at any time to the square of sound pressure at a reference distance is equal to the square of the reference distance to the square of the distance between a receiving point and a noise source at any time, which is mathematically expressed in Eqs. (1)-(2). The equivalent continuous sound level is to integrate sound pressure in Eq. (2) as shown in Eq. (3) (Barry and Reagan, 1978).

$$\frac{P^2(t)}{P_0^2} = \frac{D_0^2}{r^2(t)} \tag{1}$$

$$P^2(t) = P_0^2 \frac{D_0^2}{D^2 + x^2(t)} \tag{2}$$

$$L_{eq}(T) = 10 \log \left\{ \frac{1}{\Delta t} \int_{t1}^{t2} \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + x^2(t)} dt \right\} \tag{3}$$

The term P_0^2 / P_{ref}^2 in Eq. (3) is the reference sound energy, depending upon type of vehicle and speed. Several countries have developed their own reference sound pressure level of vehicles based upon the US Federal Highway Administration's model, as so-called reference energy mean emission level (REMEL) as shown in Eq. (4) (Menge *et al.*, 1998). Since sound energy is an antilogarithm of sound pressure level, the reference sound energy
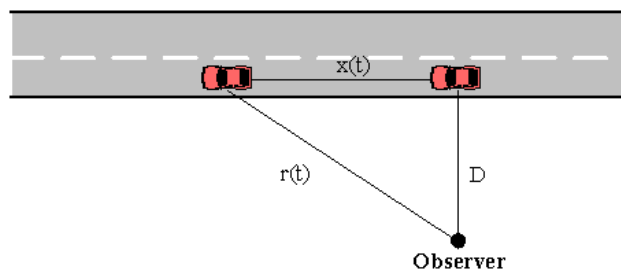

Figure 1. Propagation of sound pressure of a moving vehicle

Table 1. Coefficients of REMEL for vehicles in Thailand.

Vehicle type	Cruising condition[+]			Accelerating condition[++]		
	A	**B**	**C**	**A**	**B**	**C**
Passenger cars (PC)	5.444	59.045	-	58.691	-38.475	66.802
Light trucks (LT)	10.206	50.177	-	25.295	27.904	68.605
Medium trucks (MT)	4.437	64.965	-	30.130	23.095	71.854
Heavy trucks (HT)	9.789	57.068	-	22.881	38.887	74.902
Tractor trailers (TL)	5.692	64.842	-	19.183	50.546	77.848
Buses (BS)	11.667	52.014	-	36.866	13.448	72.665
Motorcycles (MC)	6.948	61.698	-	19.812	37.206	65.130
Tuk-tuks (TT)	-	-	-	30.253	23.554	70.375

Source: Phoowasawat (1999)[+] and Paoprayoon *et al.* (2004)[++]

(P_0^2 / P_{ref}^2) is therefore the terms in parenthesis (i.e. $10^{C/10} + 10^{(A\log S+B)/10}$).

$$L(S) = 10\log[10^{C/10} + 10^{(A\log S+B)/10}] \qquad (4)$$

In general, the REMEL is classified into two situations: cruising (uninterrupted flow) and accelerating (interrupted flow) conditions resulting two cases of coefficients *A, B* and *C*. These coefficients are obtained from field experiment. In the last part of this paper involving with the model evaluation, the values of *A, B* and *C* for vehicles in Thailand for cruising and accelerating conditions

are borrowed from the study of Phoowasawat (1999) and Paoprayoon *et al.* (2004), respectively, as shown in Table 1.

Traffic flow theories used in developing the models include characteristic of individual vehicle motion traversing an intersection, shock wave model, and queuing analysis. All of these are described through a space-time diagram as shown in Figure 2.

At the first stage, a vehicle platoon with the flow rate of q_1 veh/h and density of k_1 veh/km moves along the roadway with a constant speed. After
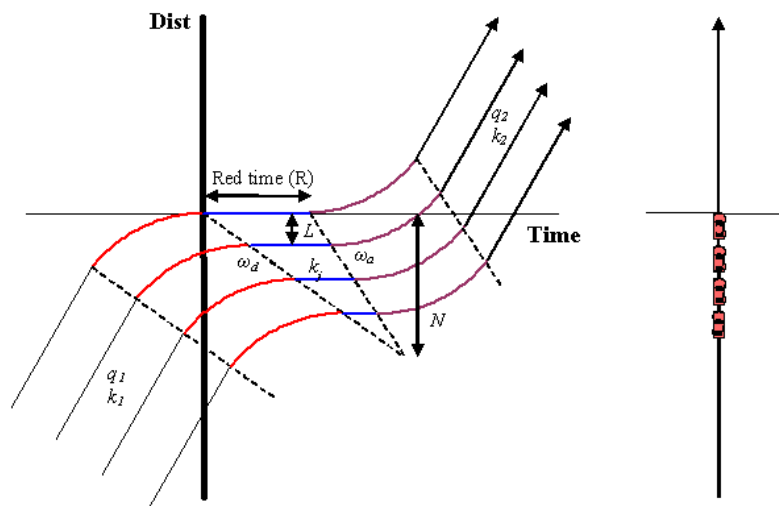

Figure 2. Space-time diagram of a vehicle platoon traversing an intersection

that, they decelerate to completely stop at the intersection. The stopping time of the first vehicle is equal to red time duration (R) and the next ones would wait for green light for unequal time periods, the last vehicle would stop for a while and then instantly accelerate. The velocity at which the first vehicle stops until the last one does is called deceleration shock wave rate (ω_d) and the velocity at which the first one begins to accelerate until the last one does is called acceleration shock wave rate (ω_a). The number of vehicles queued in a cycle is N. Shock wave rates and number of vehicles queued are calculated by applying traffic flow theories as follows (May, 1990):

$$\omega_a = -\frac{q_2}{k_j - k_2} \qquad (5)$$

$$\omega_d = -\frac{q_1}{k_j - k_1} \qquad (6)$$

$$N = \frac{R}{3600 L_V}\left(\frac{\omega_a \omega_d}{\omega_a - \omega_d}\right) \qquad (7)$$

The characteristics of vehicle motion at a signalized intersection basically consist of four regimes: cruising, deceleration, stopping, and acceleration. For deceleration and acceleration regimes, two different approaches (i.e. constant and inconstant acceleration/deceleration rates) are used to explain the movement of the vehicle platoon. The first approach assumes that acceleration/deceleration rate of each vehicle type is

constant. Another assuming that acceleration/ deceleration rate is inconstant applies nonlinear speed-distance relationship which is plotted from the field collected data.

The constant acceleration and deceleration characteristics can be explained using equations of motion in Eq. (8) and Eq. (9), respectively. During the collection of interrupted flow noise emission level, the time data while vehicles accelerate from stopping condition were recorded at the distances of 15, 30, 60, and 120 m from the stop line and were used to calculate the acceleration rate of each type of vehicle (Paoprayoon, 2004).

$$x(t) = \frac{1}{2} \times a \times t^2 \qquad (8)$$

$$x(t) = S_d \times t - \frac{1}{2} \times d \times t^2 \qquad (9)$$

The acceleration rates of vehicles in Thailand as shown in Table 2 are used for developing and evaluating models.

The inconstant acceleration and deceleration characteristics are explained through a mathematical expression in form of speed (S) in km/h as a function of traveling distance (x) in m, as shown in Eq. (10). This type of mathematical function is selected to describe the inconstant acceleration and deceleration movement because it is able to represent actual driving behavior reasonably (Paoprayoon, 2004). An example of inconstant acceleration characteristic is graphically shown in Figure 3.

Table 2. Acceleration rates of vehicles.

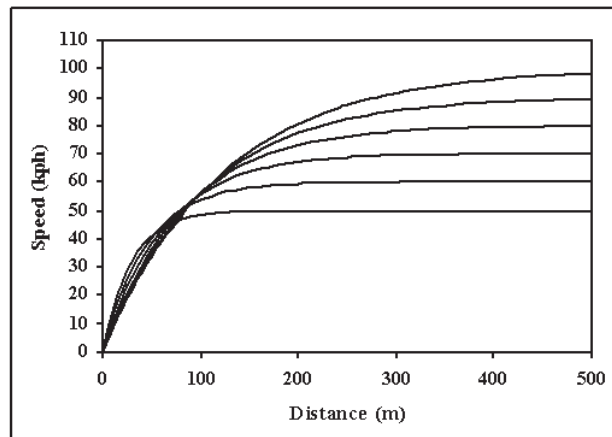| Vehicle type	Acceleration rate (m/s^2)
Passenger cars (PC)	1.50
Light trucks (LT)	1.37
Medium trucks (MT)	1.05
Heavy trucks (HT)	0.98
Tractor trailers (TL)	0.73
Buses (BS)	1.11
Motorcycles (BS)	1.31
Tuk-tuks (TT)	1.56

Source: Paoprayoon (2004)

Figure 3. Speed-distance plot for inconstant acceleration approach
Source: Paoprayoon (2004)

$$S(x) = 3.6(L - Le^{-Mx}) \qquad (10)$$

The coefficients L and M obtained from nonlinear regression analysis of field data are exhibited in Table 3.

In addition to the plot of speed vs. distance, the relationships between distance and time (x-t) and speed and time (S-t) are also necessary to traffic noise model development. Both relationships are derived by applying a basic physics theory and calculus. The derivation of x-t relationship is described through the following equations (Meriam and Kraige, 1997).

$$dx = Sdt \qquad (11)$$

$$t = \int_v^x \frac{1}{S(x)}\, dx \qquad (12)$$

$$t = \int_v^x \frac{e^{Mx}}{L(e^{Mx} - 1)}\, dx \qquad (13)$$

The result of the integration in Eq. (13) in term of $t(x)$ is then converted to $x(t)$ as follows:

$$x(t) = \frac{1}{M}\ln(e^{(LMt+k)} + 1); \quad k = \ln(e^{vM} - 1) \quad (14)$$

The S-t relationship is derived by taking the

Table 3. Coefficients of speed-distance relationship.

Type	Free Flow Speed (km/h)											
	\multicolumn{2}{c}{50}	\multicolumn{2}{c}{60}	\multicolumn{2}{c}{70}	\multicolumn{2}{c}{80}	\multicolumn{2}{c}{90}	\multicolumn{2}{c}{100}
	L	M	L	M	L	M	L	M	L	M	L	M
PC	13.889	0.058	16.667	0.038	19.444	0.026	22.222	0.019	25.000	0.014	27.778	0.012
LT	13.889	0.054	16.667	0.036	19.444	0.025	22.222	0.018	25.000	0.014	27.778	0.011
MT	13.889	0.034	16.667	0.023	19.444	0.016	22.222	0.012	25.000	0.010	27.778	0.008
HT	13.889	0.031	16.667	0.021	19.444	0.015	22.222	0.012	25.000	0.009	27.778	0.008
TL	13.889	0.023	16.667	0.015	19.444	0.011	22.222	0.009	25.000	0.007	27.778	0.006
MC	13.889	0.058	16.667	0.036	19.444	0.024	22.222	0.017	25.000	0.013	27.778	0.010
BS	13.889	0.038	16.667	0.025	19.444	0.018	22.222	0.013	25.000	0.010	27.778	0.009
TT	13.889	0.060	16.667	0.041	19.444	0.029	22.222	0.021	25.000	0.016	27.778	0.013

Source: Paoprayoon (2004)

derivative of distance (x) by time (t) as shown in Eq. (14).

$$S(t) = \frac{L.e^{LMt+k}}{e^{LMt+k}+1} \qquad (15)$$

The distances at which the vehicles arrive their cruise speeds (X) are necessary for calculating noise level, they are then calculated from Eq. (10) using Goal Seek function in MS Excel as shown in Table 4.

The inverse square law of sound pressure incorporating with REMEL and traffic flow theories as described above lead to the development of interrupted flow traffic noise models. As stated previously, the models are divided into two approaches: constant and inconstant acceleration/ deceleration, which are primarily constructed in form of sound energy. The final models are the summation of sound energy from all movement regimes and then converted to 1-hr equivalent continuous sound level (L_{Aeq} 1-hr). The formulation of sound energy of all four traffic regimes is explained as the following.

1.1 Sound Energy for Idle Condition

From Figure 2, stopping time duration (t_{idl}) of each vehicle waiting for a traffic signal is not even. The first vehicle in the platoon waits for the signal for red time (R) as shown in Eq. (16) whereas the next ones conform to Eqs. (17)-(18).

1st veh.; $\quad t_{idl(1)} = R$ $\qquad (16)$

2nd veh.; $\quad t_{idl(2)} = R - L_V / \omega_d + L_V / \omega_a$ $\qquad (17)$

Nth veh.; $\quad t_{idl(N)} = R - (N-1)L_V / \omega_d + (N-1)L_V / \omega_a$

$\qquad (18)$

Since it is impossible to identify exactly the stopping position of each vehicle in real traffic situation in which traffic combination exists, one assumes that all vehicles stop at the middle of queue length except motorcycles which practically stop at the stop line. The noise levels or sound energy of the vehicles which locate in front of the middle point of the queue are likely to compensate with those which stay behind. According to Figure 2 and Eq. (3), sound energy of the stopped vehicles can be therefore mathematically expressed as follows:

1st veh.; $\quad E_{idl(1)} = \int_0^R \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2})^2} \, dt$ $\qquad (19)$

2nd veh.; $\quad E_{idl(2)} = \int_{L_V/\omega_d}^{R+L_V/\omega_a} \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2})^2} \, dt$

$\qquad (20)$

Therefore, total sound energy of all stopped vehicles in a cycle can be summed up as follows:

Table 4. Distances from stopping condition to various cruise speeds (m)

Type	Free Flow Speed (km/h)					
	50	60	70	80	90	100
PC	210.0	270.2	493.1	716.0	844.5	931.9
LT	200.1	284.5	516.6	748.7	844.5	1011.8
MT	323.1	450.7	824.0	1197.4	1147.3	1369.9
HT	352.6	491.4	844.4	1197.4	1342.2	1369.9
TL	464.0	701.1	1099.4	1497.6	1689.1	1863.8
MC	187.4	284.5	535.0	785.6	902.7	1107.4
BS	277.2	416.5	775.5	1134.4	1147.3	1224.2
TT	181.6	251.4	456.2	661.0	749.5	864.1

Source: Paoprayoon (2004)

$$E_{idl} = \int_0^R \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2})^2} dt + \int_{L_V/\omega_d}^{R+L_V/\omega_a} \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2})^2} dt + \int_{2L_V/\omega_a}^{R+2L_V/\omega_a} \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2})^2} dt + ...$$

(21)

From Eq. (21), the result of integration is simplified as follows:

$$E_{idl} = \frac{P_0^2}{P_{ref}^2} \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2})^2} \left(N \times R + \frac{N(N-1) \times L_V}{2\omega_a} - \frac{N(N-1) \times L_V}{2\omega_d} \right)$$

(22)

1.2 Sound Energy for Acceleration Condition

Referring to Figure 2, time of acceleration of all vehicles in a traffic stream is theoretically equal. In the same manner to the idle noise level, every vehicle is assumed to accelerate from the middle of the queue and reaches the final cruise speed at the same location. Therefore, sound energy of all vehicles accelerating is calculated by multiplying sound energy of a vehicle with number of vehicle queued. As stated earlier, the model formulation of acceleration/deceleration noise level is divided into constant and inconstant acceleration/deceleration approaches.

1) Constant Acceleration Approach

The model of sound energy for constant acceleration condition is constructed based on the acceleration characteristic which is given in Eq. (8). The resultant equation is expressed as follows:

$$E_{acc} = N \int_o^{S_a/a_a} \left[10^{C_a/10} + 10^{(A_a \log(a_a t) + B_a)/10} \right] \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2} - \frac{1}{2}a_a t^2)^2} dt$$

(23)

2) Inconstant Acceleration Approach

The model of sound energy for inconstant acceleration condition is formulated in the same manner with that of constant acceleration condition. However, movement characteristic in Eqs. (10)-(15) explaining inconstant acceleration behavior is applied instead.

$$E_{acc} = N \int_o^{\frac{1}{LM}\left\{ \ln(e^{Mx}-1)-k \right\}} \left[10^{C_a/10} + 10^{\left(A_a \log \frac{L(e^{LMt+k})}{e^{LMt+k}+1} + B_a \right)/10} \right] \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2} - \frac{1}{M}\ln(e^{LMt+k}+1))^2} dt$$

(24)

1.3 Sound Energy for Deceleration Condition

Similar to acceleration condition, sound energy of every decelerating vehicle is theoretically the same. Total sound energy of decelerating vehicles is to multiply sound energy of single vehicle with number of vehicle queued. It should be noted that constant deceleration characteristic is defined by Eq. (9) and inconstant deceleration characteristic is explained by the same equation as inconstant acceleration condition. Nevertheless, the parameters L and M in Eq. (10) for deceleration situation need to be determined. Because of the difficulties in collecting deceleration behavior, one can assume to use the same values for both acceleration and deceleration conditions in case of no field data.

1) Constant Deceleration Approach

Sound energy for constant deceleration condition is constructed based on the deceleration characteristic which is given in Eq. (9), yielding the resultant model as shown in Eq. (25).

$$E_{dec} = N \int_o^{S_d/a_d} \left[10^{C_c/10} + 10^{(A_c \log(S_d - a_d t) + B_c)/10} \right] \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2} + \frac{S_d^2}{2a_d} - (S_d t - \frac{1}{2} a_d t^2))^2} dt \tag{25}$$

2) Inconstant Deceleration Approach

The model of sound energy for inconstant deceleration condition is very similar to that of inconstant acceleration condition. However, coefficients of REMEL for cruising condition (A_c, B_c and D_c) and applied instead, meaning that noise emission level of a vehicle in decelerating and cruising situations is presumably equal. This assumption is also employed in Traffic Noise Model 1.0 (TNM 1.0), the latest version of US Federal Highway Administration's traffic noise model (Menge *et al.*, 1998).

$$E_{dec} = N^{\frac{1}{LM}} \int_o^{\frac{1}{LM}\{\ln(e^{Mx} - 1) - k\}} \left[10^{C_c/10} + 10^{(A_c \log \frac{L(e^{LMt+k})}{e^{LMt+k}+1} + B_c)/10} \right] \frac{D_0^2}{D^2 + (J + \frac{L_Q}{2} - \frac{1}{M}\ln(e^{LMt+k} + 1))^2} dt \tag{26}$$

1.4 Sound Energy for Cruising Condition

Traffic noise in cruising condition is emitted from two vehicle groups. The first is the vehicles which cruise through an intersection with a constant speed without the effects of red light and vehicle queue. Another is the vehicles which are queued at the intersection because they initially travel with a constant speed before decelerating and stopping at the intersection. After the disappearance of red time, they accelerate and reach a constant speed again. The duration for which the first vehicle group travels in cruising condition is an hour, but that for which another group travels in cruising condition is then an hour subtracted by stopping time, deceleration time, and acceleration time. The models of sound energy for both cruising vehicle groups are mathematically shown in Eqs. (27)-(28).

$$E_{cru(1)} = N_C \int_{-1800}^{1800} [10^{C_c/10} + 10^{(A_C \log S_{av} + B_C)/10}] \frac{D_0^2}{D^2 + (S_{av} t)^2} dt \tag{27}$$

$$E_{cru(2)} = N \int_{-1800}^{1800-(R+S_d/d+S_a/a)} [10^{C_c/10} + 10^{(A_C \log S_{av} + B_C)/10}] \frac{D_0^2}{D^2 + (S_{av} t)^2} dt \tag{28}$$

$$N_C = \frac{1}{2N_{cy}}(q_1 + q_2) - N \tag{29}$$

Total sound energy of all vehicles in cruising condition in a cycle is the summation of $E_{cru(1)}$ and $E_{cru(2)}$ as follows:

$$E_{cru} = E_{cru(1)} + E_{cru(2)} \tag{30}$$

The equivalent continuous sound level of the interrupted traffic in L_{Aeq} (1hr) is the summation of sound energy from all movement regimes (i.e. idle, acceleration, deceleration, and cruising) and converted to sound pressure level in logarithmic scale as follows:

$$L_{Aeq}(1hr) = 10 \log \left\{ \frac{1}{T_C} \left(\sum_{all(i)} E_{idl(i)} + \sum_{all(i)} E_{acc(i)} + \sum_{all(i)} E_{dec(i)} + \sum_{all(i)} E_{cru(i)} \right) \right\} \tag{31}$$

Since the developed model consists of complicated mathematical functions, resulting manual calculation impossible, a computer programme in Visual Basic 6.0 is then developed to help users analyze traffic noise level at an intersection conveniently.

2. Evaluation of Models

As described in the previous section, the developed models are classified into two approaches corresponding to the differences in vehicle movement characteristics (i.e. constant and inconstant acceleration/deceleration approaches). Therefore, the validity and accuracy evaluation needs to be performed to reveal the capability of prediction between the two. The models are evaluated by means of comparing the predicted noise levels with the measured ones by collecting equivalent continuous noise levels in 1 minute (L_{Aeq} 1 min) of single-type vehicle platoons and relevant traffic flow parameters. The L_{Aeq} 1 min was measured by using three sound level meters. One of them was located at the stop line and others were located at the distances of 15 m upstream and downstream from the stop line with 15 m setback from the centerline of travel lane as illustrated in Figure 4. The locations at which the experiment was performed are rural and suburban two-lane highways in these provinces, namely,

Bangkok, Nakornpathom, and Suphanburi.

In the experiment, the researcher would select vehicle platoons consisting of two or more vehicles. A crew would block the selected platoon to stop at the stop line. After all of them stopped completely, the L_{Aeq} 1 min would be recorded simultaneously using the three instruments. During the measurement of L_{Aeq}, the first vehicle would be idle for an assumed red time (30 sec) whereas the other crews would count number of vehicles in the platoon and measured the length of the queue (the distance between the front of the first vehicle and the front of the last one). After 30 sec, the vehicles would be allowed to accelerate. The time at which the first vehicle began to accelerate until the last one did was also recorded for calculating acceleration shock wave rate. When the platoon reached a constant speed, a crew would measure the speed of the first vehicle which was assumed to be the cruise speed of the platoon. The field traffic parameters incorporating with interrupted and idle noise emission levels from the findings of Paoprayoon (2004) as well as uninterrupted noise emission levels from Phoowasawat (1999) were employed as the inputs of the developed models. Finally, traffic noise levels predicted from the developed models were compared with those from the measured ones to determine the accuracy and validity of the models.
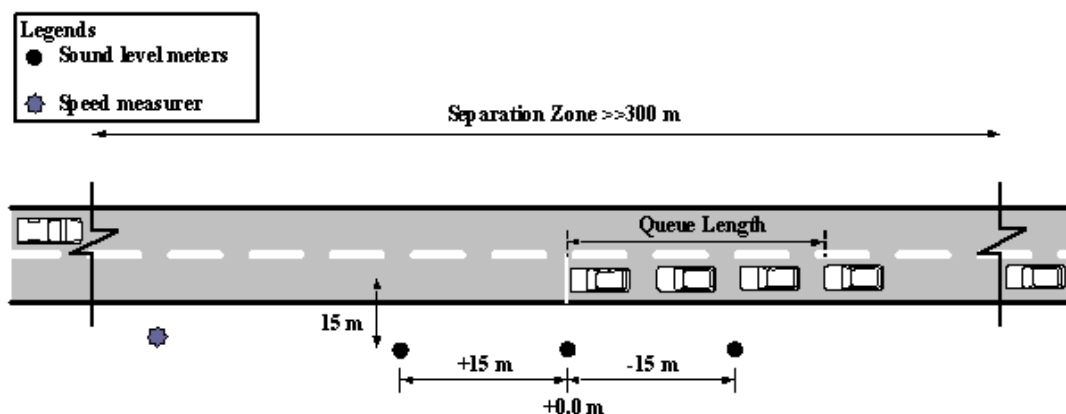

Figure 4. A site layout of data collection for model evaluation

3. Equipments

The equipments used in the study consist of three sound level meters, a measuring tape (50 m), a spray paint, and three stopwatches.

Results

From the theories and research methodology discussed earlier, the final model of interrupted traffic noise at a signalized intersection is the summation of sound energy from all movement regimes and then converted to one hour equivalent continuous sound level as expressed in the following equation.

$$L_{Aeq}(1hr) = 10\log\left\{\frac{1}{T_C}(\sum_{all(i)} E_{idl(i)} + \sum_{all(i)} E_{acc(i)} + \sum_{all(i)} E_{dec(i)} + \sum_{all(i)} E_{cru(i)})\right\} \tag{32}$$

However, there are two types of sound energy models for acceleration and deceleration conditions depending upon the user's purposes. The constant acceleration/deceleration model is more convenient and requires less number of input parameters than the inconstant acceleration/deceleration model. However, the accuracy of the constant acceleration model is somewhat lower than the inconstant acceleration/deceleration model, as discussed in detail hereafter.

Traffic noise levels are forecasted using traffic flow and noise data of fifteen platoons from three instruments located at -15, 0, and 15 m from the stop line. The model evaluation is then performed through the comparison between the predicted levels from both approaches and the measured ones as shown in Figures 5-7.

As Figures 5-7 show, it is apparent that the measured noise levels do agree well with the predicted levels from inconstant acceleration approach (Approach 2) rather than constant acceleration approach (Approach 1). The error of the inconstant acceleration model ranges from 0.1-3.9 dB(A) with the average value of 2 dB(A) overestimated and that of another model ranges from 1.8-6.5 dB(A) with the average value of 3 dB(A) underestimated. This is because the acceleration rates of inconstant acceleration characteristic which is explained through the speed-distance relationship in Eq. (10) are higher than
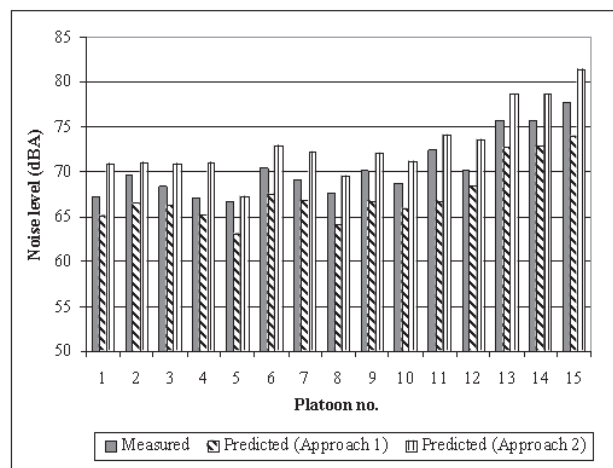

Figure 5. Comparison between predicted and measured L_{Aeq} 1 min at 15 m upstream from the stop line
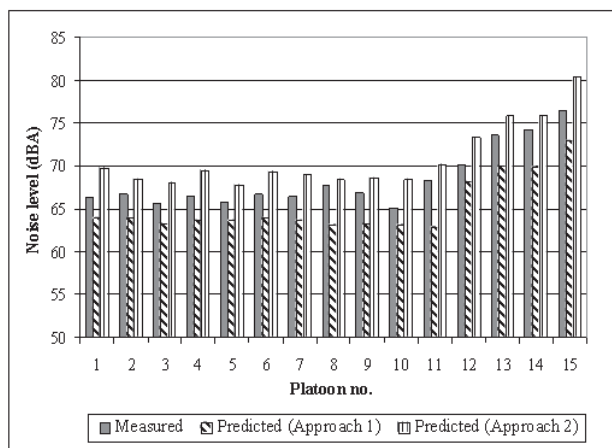
Figure 6. Comparison between predicted and measured L_{Aeq} 1 min at the stop line
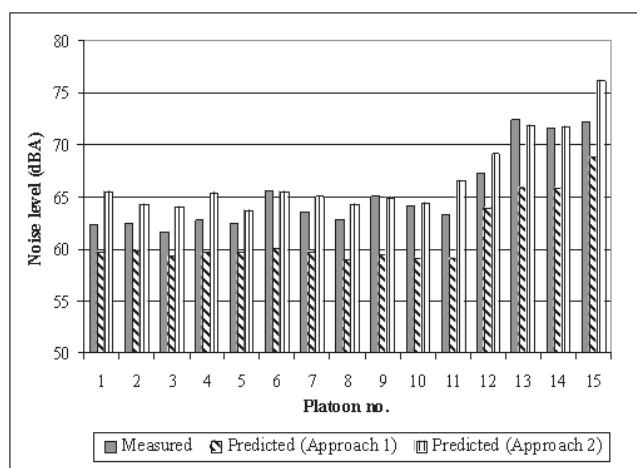

Figure 7. Comparison between predicted and measured L_{Aeq} 1 min at 15 m downstream from the stop line

constant acceleration rate in Table 2, resulting in the higher predicted noise values.

Conclusions

This research attempts to initiate a new methodology and models for forecasting traffic noise levels at a signalized intersection in the form of L_{Aeq} 1-hr. The developed models are classified into two approaches corresponding to movement characteristics of vehicles: constant and inconstant acceleration/deceleration. The models are initially constructed from the inverse square law of sound pressure incorporating the traffic flow parameters (e.g. shock wave model, queuing model, physical vehicle motion) by applying both calculus and numerical analysis. The resultant models can estimate the sound energy of vehicles in idle, decelerating, accelerating, and cruising conditions separately. The equivalent continuous sound level in an hour (L_{eq} 1hr) is derived as a final model by summing sound energy from all regimes and then converting to sound pressure levels.

Finally the constructed models are evaluated by comparing the predicted levels to the measured ones. The result reveals that the inconstant

acceleration approach gives the more accurate values compared with the measured data. The error of the inconstant acceleration model ranges from 0.1-3.9 dB(A) with the average value of 2 dB(A) overestimated and that of constant acceleration model ranges from 1.8-6.5 dB(A) with the average value of 3 dB(A) underestimated. It might be concluded that the movement characteristic of vehicle is an important factor that apparently affects the accuracy of the traffic noise prediction at the intersections.

Recommendations for Future Works

Corresponding to the problems existing in this research, the authors would like to give the recommendations for the future researches as the following.

1) The deceleration rate or speed-distance relationship in decelerating condition of each vehicle type should be collected. However, it should be noted that the measurement of deceleration rate is much more difficult. Applying other more effective techniques like GPS technology can result in more accurate data.

2) The data from multi-type platoons should be collected for model evaluation to ensure that the models can predict such the traffic situation accurately.

3) Some correction factors should be explored to improve the accuracy of the models.

4) The models should be further developed by taking into account of the effects of barriers and buildings.

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Notation

The following symbols are used in this paper:

a_a = acceleration rate (m/s^2)

a_d = deceleration rate (m/s^2)

A_a, B_a, C_a = coefficients of accelerating noise emission model

A_c, B_c, C_c = coefficients of uninterrupted noise emission model

D = perpendicular distance between the observer and the centerline of travel lane (m)

D_0 = reference distance, usually 15 m

e = exponential

i = vehicle type

J = distance between an observer and a stop line (m), (+) if measured in the same direction of traffic flow, (-) if measured in the opposite direction of traffic flow

k_1, k_2 = traffic densities before approaching and after departing an intersection, respectively (veh/km)

k_j = jam traffic density (veh/km)

$L(S)$ = reference energy mean emission level or basic noise emission level as a function of speed (dBA)

L, M = coefficients of speed-distance relationship

L_Q = queue length (m)

L_V = average length of each type of vehicle plus gap in stopping condition (m)

N = number of vehicles queued in a cycle (veh)

N_C = number of vehicles cruising through an intersection in a cycle (veh)

N_{cy} = number of signal cycle in an hour

$p(t)$ = sound pressure at time t (N/m^2)

p_0 = sound pressure at a reference distance (N/m^2)

p_{ref} = reference sound pressure equal to 2×10^{-5} N/m^2

q_1, q_2 = traffic flow rates before approaching and after departing an intersection, respectively (veh/h)

$r(t)$ = distance between an observer and a noise source (m)

R = red time (sec)

S_a = constant speed after acceleration (m/s)

S_d = constant speed before deceleration (m/s)

S_{av} = average constant speed (m/s), equal to $1/2\,(S_a + S_d)$

$S(t)$ = vehicle speed at time t (m/s)

$S(x)$ = vehicle speed as a function of distance from a stop line (m/s)

t = time (sec)

T_C = cycle length (sec)

x = distance from a stop line (m)

X = distance between a stop point and the point at which a vehicle reaches a constant speed in accelerating condition, or distance between the last point at which a vehicle still maintains constant speed before deceleration and a stop point (m)

ω_a = accelerating shock wave rate (m/s)

ω_d = decelerating shock wave rate (m/s)

v = lower limit of integral very close to zero