# A PRELIMINARY CALIBRATION EXERCISE OF HDM-4'S ROAD USER EFFECT RELATIONSHIPS FOR JAPANESE CONDITIONS

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## ABSTRACT

The Highway Development and Management Tool (HDM-4) is a state-of-the-art tool for road investment decision analysis based on the comparative evaluation of costs and benefits of alternative investment strategies. The costs and benefits of the alternative investment strategies are estimated using relationships classified under two broad categories: Road User Effects (RUE) and Road Deterioration and Works Effects (RDWE). Relationships under the RUE include models to estimate vehicle operating costs (VOC), travel time and exhaust emissions, whereas relationships under the RDWE include models to predict the deterioration of pavement and the impacts of maintenance activities on the pavement condition. The RUE components are estimated as a function of factors such as vehicle characteristics, pavement condition, etc., whereas the RDWE are predicted as a function of factors such as environmental conditions, traffic characteristics, etc. As these factors vary from country to country, local calibration of both the RUE and RDWE relationships is a prerequisite for a sound road investment decision-making. The transferability of the HDM-4 tool across countries to suit local conditions is ensured through a set of calibration factors that are adjusted in such a manner that the differences between the estimated RUE and RDWE components and the observed ones are minimized. This paper presents the results of a preliminary calibration exercise, one of the first in Japan, of the RUE relationships of five typical vehicles i.e., small passenger cars, medium passenger cars, medium trucks, heavy trucks and heavy buses. The basic input data required for the calibration were obtained from reports published by the Japanese trucks and buses operating companies, car dealers, etc., and earlier studies on VOC and exhaust emissions undertaken by different Japanese government agencies. Calibration factors were estimated for the parts consumption and labour hours for the VOC relationships and for the nitrous oxide, carbon monoxide, hydrocarbon, particulates, carbon dioxide and sulphur dioxide exhaust for emissions relationships. It was found that the use of HDM-4 default parameters overestimates both the parts consumption and labour hours in comparison to the actual consumption in Japan for all the five vehicle types considered. However, the estimates of the exhaust emissions were found to be less for some vehicles and high for others.

## KEY WORDS

HDM-4 CALIBRATION / ROAD USER EFFECTS / VEHICLE OPERATING COSTS / EXHAUST EMISSIONS / JAPAN.

## 1. INTRODUCTION

The Highway Development and Management tool (HDM-4) is a state-of-the-art tool for road investment decision analysis based on the comparative evaluation of costs and benefits of alternative investment strategies. The strategies are compared by calculating the discounted total transport cost (sum of construction cost, maintenance cost, road user cost, etc.) of alternative strategies over a specified period of analysis. The components of the total transport cost are obtained by multiplying the unit prices and physical quantities of resource consumption, which are predicted using relationships classified under two broad categories: Road User Effects (RUE) and Road Deterioration and Works Effects (RDWE). Relationships under RUE include models to estimate vehicle operating costs (VOC), travel time and exhaust emissions, whereas relationships under RDWE include models to predict the deterioration of the pavement and the impact of maintenance on pavement conditions.

The development of these models has spanned the last three decades (from the Highway Cost Model (Moavenzadeh, 1971) to HDM-4 (2002)), and during this period the form of the models and the level of sophistication to formulate them has advanced from empirical regression models established using data collected at specific sites, to structural mechanistic empirical models established using advanced rigorous statistical analysis utilising real data gathered from a wide range of vehicle types and road conditions. The mechanistic empirical form of the HDM-4 relationship gives it the flexibility of being able to be used in different countries by providing local inputs. Still, the HDM-4 study identifies that even though the field experiments covered a wide range of conditions, and even though state-of-the-art technology was applied in the model's development, there remained some factors that could not be introduced, because they were not measured or would have made the model's input too complex, or because their effects could not be determined within the ranges observed. Also there have been advances in vehicle technology in the period since the studies were carried out which have lowered consumption and operating costs, making HDM-4 calibration both sensible and desirable (Bennett and Paterson, 2002). This paper presents the results of a preliminary calibration exercise of RUE relationships for five vehicle types to Japanese conditions.

## 2. CALIBRATION LEVEL AND SENSITIVITY CLASSES

In contrast to the Highway Design and Maintenance Standards Model (HDM-III, Watanatada, et al., 1987), HDM-4 deals with the model calibration in a more systematic way by dividing it into three levels depending on the efforts and resources involved. The division is as follows (Bennett and Paterson, op cit.):
Level 1 – Basic Application: Determines the values of required basic input parameters, adopts many default values, and calibrates the most sensitive parameters with the best estimates, desk studies or minimal field surveys
Level 2 – Calibration: Requires measurement of additional input parameters and moderate field surveys to calibrate key predictive relationships to local conditions. This level may entail a slight modification to the HDM-4 source code.
Level 3 – Adaptation: Undertakes major field surveys and controlled experiments to enhance the existing predictive relationships or to develop new and locally specific relationships for substitution in the source code of the HDM-4 tool.

In addition to the calibration levels, HDM-4 also identifies the sensitivity of the model to each parameter so that appropriate focus can be given to each parameter depending on its sensitivity. The parameters are classified under four sensitivity classes, S-I to S-IV, and the impact of the parameter decreases with the decrease in the class number. Based on the sensitivity class numbers, the HDM-4 study recommends priorities for parameters to be calibrated under the three calibration levels as shown in Figure 1. This study primarily deals with the level 1 calibration and briefly covers level 2 calibration.

## 3. INPUT PARAMETERS (VEHICLE CHARACTERISTICS & UNIT PRICES)

Running the HDM-4 tool requires specification of input data for representative vehicles. Based on the number of vehicles registered in Japan (see Table 1), the following five types of representative vehicles were adopted in this study: small car, medium car, medium truck, heavy truck and heavy bus. Based on the market share of the different vehicle manufacturers, the best-selling model was identified for each representative vehicle type for obtaining vehicle characteristics data. Through a combination of interviews and questionnaire surveys with bus drivers, tyre shops, trucking companies, bus operating companies, vehicle dealers and distributors, information available in research reports and motor vehicle magazines and studies undertaken by different governmental agencies, vehicle characteristics data for the representative vehicles was obtained as listed in Table 2 along with brief notes on the sources.

This study compares HDM-4 VOC outputs with an earlier research study which quantified the different VOC components in the financial costs. Thus, financial costs instead of economic ones are used in this study[1)]. Again, relying on market surveys and available literature, cost data was obtained for the representative vehicles as listed in Table 3.

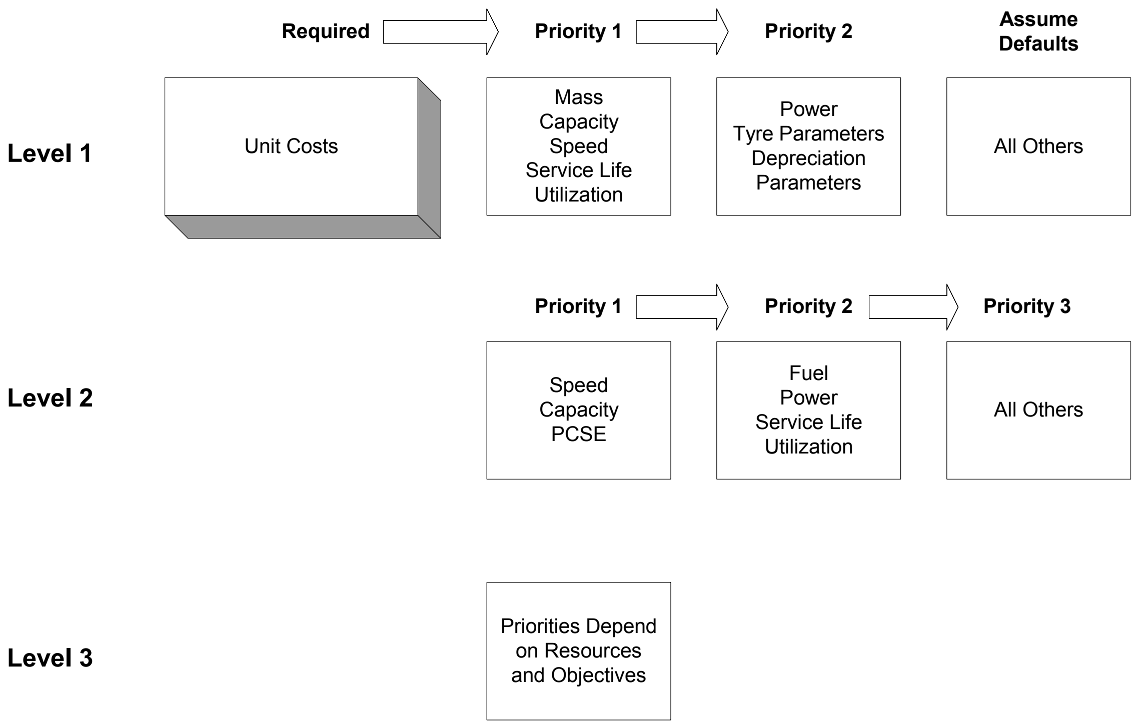


Figure 1 - Calibration priorities (Source: Bennett and Paterson (2002))

## 4. COMPARISON OF HDM-4 OUTPUTS WITH EARLIER STUDIES

### 4.1. VOC Comparison

HDM-4 VOC outputs were compared with an earlier study undertaken by the Mitsubishi Research Institute (MRI) for the Japanese Ministry of Land, Infrastructure and Transport (MRI, 2003). The MRI study observed the VOC for national and provincial roads, and roads in mountainous terrain, for four types of vehicle (cars, medium and heavy trucks and heavy buses) at different speeds. This study used VOC data for the smooth national roads

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1) Economic costs were also calculated for most of the parameters and are available from the authors.

from the MRI study. Therefore, straight and level road geometry with low traffic were the assumed characteristics of the road section in the HDM-4 simulations.

Table 1 - Number of registered vehicles in Japan

| Type | | Personal | Commercial |
|---|---|---|---|
| Truck | Normal | 1,628,626 | 890,009 |
| | Small | 4,988,777 | 76,881 |
| Bus | Normal | 26,069 | 83,953 |
| | Small | 105,152 | 17,754 |
| Car | Normal | 155,390,993 | 34,189 |
| | Small | 27,161,621 | 227,927 |
| | Light | 11,796,326 | |
| Utility | Normal | 971,371 | 234,294 |
| | Small | 186,749 | 12,560 |
| | Special type | 320,869 | 3,419 |
| Motor Bike | Small | 1,373,055 | |
| | Light | 1,788,949 | |

Source: AIRA (2003)

Figures 2 to 5 compare MRI VOC measurements with those obtained from the HDM-4 simulations for the four vehicle types. The HDM-4 predictions are higher than the MRI measurements for all VOC components except tyre consumption. The difference is most pronounced for maintenance costs (sum of parts and labour costs), which is not surprising as the HDM-4 relationships for predicting parts consumption and labour hours were developed in the context of economies with very different characteristics from those in Japan (i.e. difference in labour wages, vehicle age, and other operating characteristics, etc.). On the other hand, the depreciation costs are in agreement, particularly for trucks and buses, revealing the importance of local input data for annual utilisation, service life and hours worked which are needed to calculate depreciation. The difference is higher for medium cars as the hours worked were estimated by dividing the annual kilometres driven for these cars with the average speed of trucks and buses, assuming that the average car speed is the same as that of the average speed of trucks and buses (see Table 2, note 12).

Figures 6 to 9 compare the fuel consumption predicted by HDM-4 and MRI values for the four vehicle types at different speeds. For all vehicles, the HDM-4 predictions are higher than the MRI values, which is understandable as vehicle technology is continuously advancing and resulting in vehicles which consume less fuel. However, the shape of the two fuel consumption curves for measurements made at different speeds are very similar for all vehicle types. Since the HDM-4 fuel prediction model is of mechanistic type, it is highly possible that detailed calibration would result in closing the translation gap between the HDM-4 predictions and the MRI values.

Calibration of the maintenance costs requires splitting the cost into parts and labour costs. The MRI study gives estimates of the total maintenance cost only, and does not identify the split between the two. The share of parts, as obtained from the HDM-4 predictions, varies from 16% to 33% for medium cars and heavy trucks respectively. In the absence of better estimates, though a crude approach, the share as obtained from HDM-4 for each vehicle was used to split MRI maintenance cost into parts and labour costs. Parts consumption and labour hours, without considering the influence of speed change cycles, for a given vehicle type are calculated in the HDM-4 as follows:

## Table 2 - Characteristics of Representative Vehicles

| Type | Fuel Type[1)] | No. of Axles[2)] | No. of Wheels[2)] | No. of Passengers[3)] | Tyre Type[4)] | Tyre wearable rubber volume[5)] ($dm^3$) | Base no. of Recaps[6)] | Retread Cost[6)] | Projected Frontal Area[7)] ($m^2$) | Operating Weight[8)] (tonnes) | ESAL factor[9)] | PCSE[10)] | Annual Kilometres Driven[11)] | Annual Working Hours[12)] | Service Life[13)] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Small Car** | P | 2 | 4 | 1.6 | R | 1.27 | N/A | N/A | 2.42 | 0.875 | 0.000 | 1.0 | 8479 | 184.5 | 10 |
| **Medium Car** | P | 2 | 4 | 1.6 | R | 1.9 | N/A | N/A | 2.49 | 1.135 | 0.000 | 1.0 | 10519 | 228.9 | 10 |
| **Medium Truck** | D | 2 | 6 | 1.4 | R | 4.64 | N/A | N/A | 8.75 | 5.340 | 0.076 | 1.6 | 45400 | 2113 | 10 |
| **Heavy Truck** | D | 3 | 10 | 1.2 | R | 8.12 | N/A | N/A | 9.25 | 16.040 | 4.188 | 1.9 | 150000 | 2173 | 10 |
| **Heavy Bus** | D | 2 | 6 | 21.9 | R | 7.17 | N/A | N/A | 7.80 | 12.765 | 1.680 | 1.7 | 60000 | 1267 | 10 |

1) P stands for Petrol and D for Diesel.
2) Data for small and medium cars is based on the vehicle's introductory literature published by vehicle manufacturers (Suzuki and Toyota), whereas data for trucks and heavy buses are based on data published by the Expressway Technical Center.
3) Based on weekday traffic from 1994 Highway Traffic Census.
4) Based on the vehicle's introductory literature published by vehicle manufacturers [Suzuki (Wagon-R for small car), Toyota (Corolla for medium car), Hino, Isuzu and Mitsubishi (for trucks and heavy buses)].
5) Calculated using the relationship given in Bennett and Paterson (2002). Inputs such as the nominal width of the tyre, rim size and aspect ration were obtained from the product's introductory literature published by the vehicle manufacturers and tyre manufacturers.
6) N/A stands for not applicable. Re-treading is not a common practice in Japan.
7) Based on the vehicle's introductory literature published by Suzuki and Toyota manufacturers for small and medium cars; based on surveys of trucking companies for trucks, and based on data available at Mitsubishi motors homepage for heavy buses.
8) Calculated using vehicle tare weight obtained from the vehicle's introductory literature published by the vehicle manufacturers, and percentage of loaded vehicle obtained from 1994 Highway Traffic Census data.
9) Calculated using the relationship given in Bennett and Paterson (2002). Inputs to the relationship included the operating weight as obtained in 8), and the distribution of loads on different axles, which was obtained from the data published by Expressway Technical Center.
10) Calculated using the relationship given in Hoban et al. (1994) using the average length of vehicles obtained from the vehicle's introductory literature published by the vehicle manufacturers.
11) For cars, based on UCIM (2002). For trucks, based on surveys of trucking companies, and for heavy buses based on interviews with bus drivers.
12) For trucks and heavy buses, based on AJTA (2000). For cars, obtained by dividing the annual kilometres driven by cars with the average speed of trucks and heavy buses, assuming that the car speed in traffic is the same as that of the average of bus and trucks.
13) For cars, based on interviews with car dealers, and for heavy buses and trucks, based on surveys of bus and trucking companies.

## Table 3 - Unit costs of Representative Vehicles and Other Related Items

| Type | Crew Wages[1)] (Yen/hr) | Maintenance Labour[1)] (Yen/hr) | Passenger Working Time[1)] (Yen/hr) | Passenger Non-Working Time[1)] (Yen/hr) | Cargo Time[1)] (Yen/hr) | New Vehicle Price[2)] (Yen) | Replacement Tyre Price[3)] (Yen) | Fuel[1)] (Yen/litre) | Lubricating Oil[4)] (Yen/litre) |
|---|---|---|---|---|---|---|---|---|---|
| **Small Car** | N/A | 5384.64 | 2802 | 1954.8 | N/A | 1260000 | 4000 | 95.2 | 550 |
| **Medium Car** | N/A | 5384.64 | 2802 | 1954.8 | N/A | 1460000 | 9000 | 95.2 | 550 |
| **Medium Truck** | 4729.8 | 5384.64 | N/A | 1954.8 | 0.648 | 5500000 | 17500 | 76.1 | 550 |
| **Heavy Truck** | 4570.2 | 5384.64 | N/A | 1954.8 | 0.648 | 13000000 | 30000 | 76.1 | 550 |
| **Heavy Bus** | 3933 | 5384.64 | 2802 | 1954.8 | N/A | 20000000 | 26000 | 76.1 | 550 |

1) Based on MRI (2003).
2) Based on the vehicle's introductory literature published by vehicle manufacturers [Suzuki (Wagon-R for small car), Toyota (Corolla for medium car), Hino, Isuzu and Mitsubishi (for trucks and heavy buses)].
3) Based on an interview survey of tyre shops.
4) Based on an interview survey of oil shops and questionnaire surveys of trucking companies.

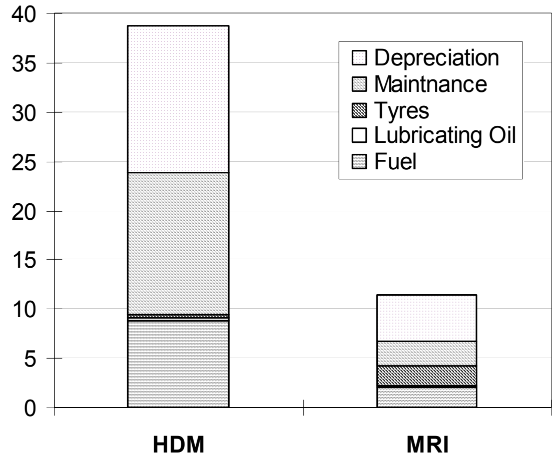


Figure 2 – VOC for medium car

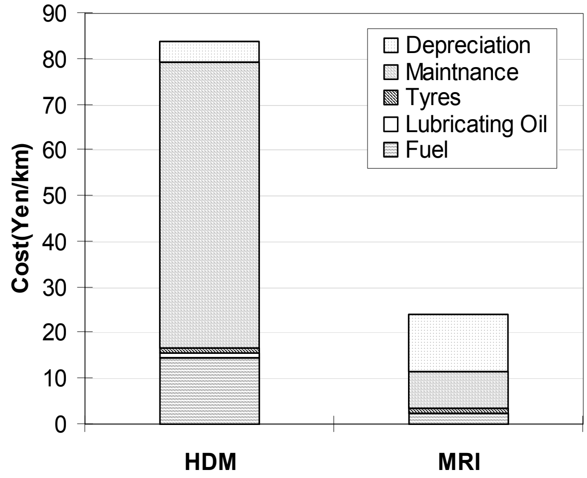


Figure 3 – VOC for medium truck

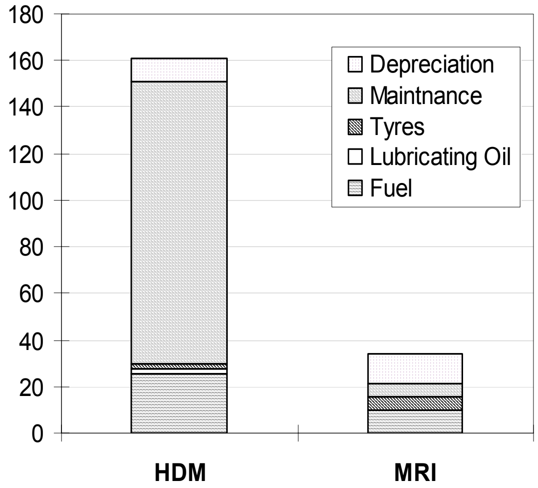


Figure 4 – VOC for heavy truck

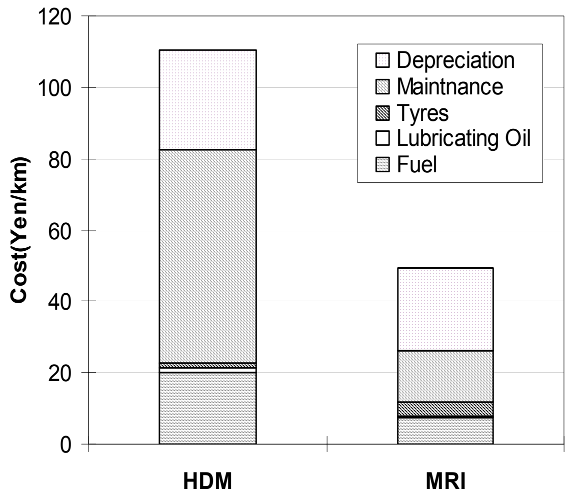


Figure 5 – VOC for heavy bus

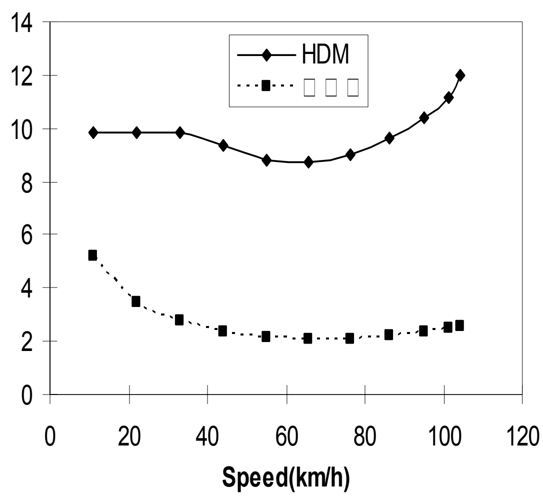


Figure 6 – Fuel Consumption for medium car

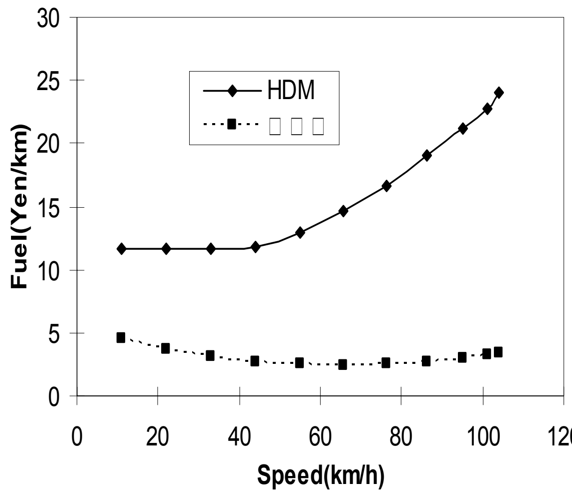


Figure 7 – Fuel Consumption for medium truck

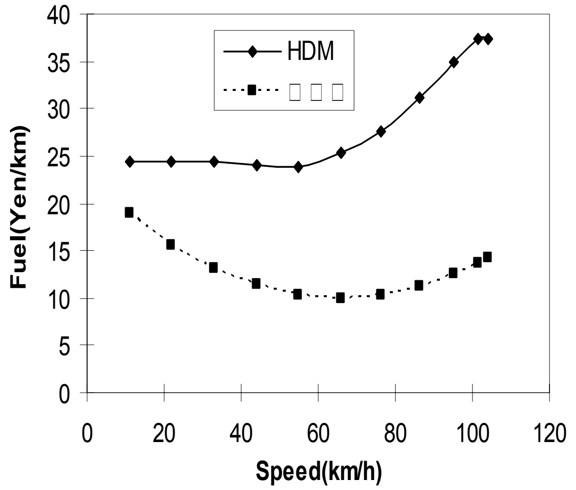


Figure 8 – Fuel Consumption for heavy truck

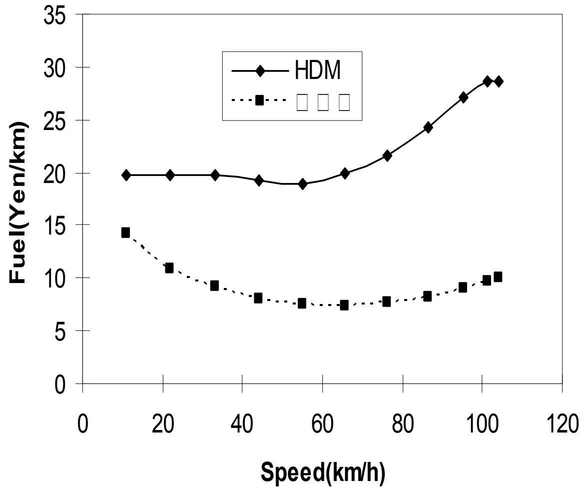


Figure 9 – Fuel Consumption for heavy bus

$$PC = K_o^p \{CKM^{kp} (a_o + a_1 RI_{adj}) + K_1^p\}$$
$$LH = K_o^l (a_2 \, PC^{a_3}) + K_1^l$$

where, PC is parts consumption as a fraction of the average new vehicle price, CKM is the average cumulative number of kilometres driven by the vehicle, kp is the age exponent, $RI_{adj}$ is the adjusted road roughness, $a_0$ and $a_1$ are the constants, and $K_o^p$ and $K_1^p$ are the rotational and translational part consumption calibration factors, respectively; LH is the number of labour hours, $a_2$ is the constant term and $a_3$ is the parts exponent of the maintenance labour model, and $K_o^l$ and $K_1^l$ are the rotational and translational labour hours calibration factors, respectively.

Calibration of all four factors ($K_o^p, K_1^p, K_o^l, K_1^l$) requires detailed data identifying the influence of adjusted roughness, vehicle age and utilisation on parts consumption and labour hours. With the limited data available, such an exercise was not possible. Thus, $K_1^p$ and $K_1^l$ were left at the default values of 1 and adjustments were made to $K_o^p$ and $K_o^l$. The adjusted factors are listed in Table 4.

4.2. Exhaust Emissions Comparison & Calibration

HDM-4 predicts exhaust emissions as a function of fuel consumption and vehicle speed. It considers seven different components of exhaust emissions, including: Hydrocarbon (HC), Carbon monoxide (CO), Nitrous oxide ($NO_X$), Sulphur dioxide ($SO_2$), Carbon dioxide ($CO_2$), Particulates (Par) and Lead (Pb). As lead-free petrol is used in Japan, calibration of Pb is not considered in this study. For rest of the exhaust emissions, the HDM-4 predictions are compared with an earlier study (TMRI, 1994) and calibration factors are obtained for the four vehicle types (small car, medium car, heavy truck and medium bus).

The HDM-4 predictions were found to be on the high side for most of the components of exhaust emissions for all the four types of vehicles, with the exception of predictions for Par which were on the lower side for all types, and $SO_2$ which were also on the lower side for all types except small car. Calibration of HC, CO, $NO_X$ and Par requires adjustment of

$K_0$ and $K_1$ (see equations (1) and (2)), and that of $SO_2$ (see equation (3)) and $CO_2$ (see equation (4)) requires adjustment of $K_o$ only.

HC, CO and $NO_X$ emissions = $$\frac{3.6\,K_o\,(a_o + a_1 K_1 IFC)(1 + 0.5\,a_2\,LIFE) * 1000}{Speed} \quad (1)$$

Par emissions = $$\frac{3.6\,K_o\,(a_o + a_1 K_1 IFC) * 1000}{Speed} \quad (2)$$

$SO_2$ emissions = $$\frac{3.6\,K_o\,a_o\,a_1\,IFC * 1000}{Speed} \quad (3)$$

$CO_2$ emissions = $$\frac{3.6\,K_o\,a_o\,IFC * 1000}{Speed} \quad (4)$$

where, IFC is instantaneous fuel consumption, LIFE and Speed are the vehicle service life and speed, $a_0$ to $a_2$ are the model parameters and $K_o$ and $K_1$ are the calibration factors for given exhaust emissions.

$K_0$ may be interpreted as a rotational calibration factor for a given exhaust emission, whereas $K_1$ is a multiplicative factor for the instantaneous fuel consumption, which is an explanatory variable in the exhaust emissions models. Calibration of both ($K_o$ and $K_1$) for HC, CO and $NO_X$ requires data identifying the influence of IFC, LIFE and Speed on the emissions. As such detailed data was not available, $K_1$ was left at its default value of 1 and calibration was carried out for $K_0$. $K_0$ was adjusted in such a manner that the sum of the square of the difference between the HDM-4 predictions and the TMRI values for the different speeds was minimised. Table 4 lists adjusted $K_0$ values for the six exhaust emissions for the four types of vehicles considered. Figures 10 to 15 plot exhaust emissions from the TMRI study and calibrated HDM-4 predictions for medium cars. The shape of the two exhaust emission curves seem to agree for all emissions, and it may be possible to reduce the discrepancy by adjusting $K_1$, except for Par emissions for which the model itself will need re-evaluation.

Table 4 - Calibration factors

| | | **Small Car** | **Medium Car** | **Medium Truck** | **Heavy Truck** | **Heavy Bus** |
|---|---|---|---|---|---|---|
| **Parts** | Rotational | 0.181[1)] | 0.181 | 0.126 | 0.048 | 0.242 |
| | Translational | 0 | 0 | 0 | 0 | 0 |
| **Labour** | Rotational | 0.459[1)] | 0.459 | 0.370 | 0.232 | 0.503 |
| | Translational | 0 | 0 | 0 | 0 | 0 |
| **HC** | K0 | 0.039 | 0.027 | 0.592[2)] | 0.592 | 0.806 |
| | K1 | 1 | 1 | 1 | 1 | 1 |
| **CO** | K0 | 0.093 | 0.063 | 0.413[2)] | 0.413 | 0.632 |
| | K1 | 1 | 1 | 1 | 1 | 1 |
| **$NO_X$** | K0 | 0.088 | 0.084 | 0.379[2)] | 0.379 | 0.659 |
| | K1 | 1 | 1 | 1 | 1 | 1 |
| **Par** | K0 | 2.822 | 3.714 | 1.559[2)] | 1.559 | 1.287 |
| | K1 | 1 | 1 | 1 | 1 | 1 |
| **$CO_2$** | K0 | 0.204 | 0.272 | 0.152[2)] | 0.152 | 0.259 |
| **$SO_2$** | K0 | 0.515 | 1.321 | 2.656[2)] | 2.656 | 4.646 |

1) Assumed same as that of medium car.
2) Assumed same as that of heavy truck.

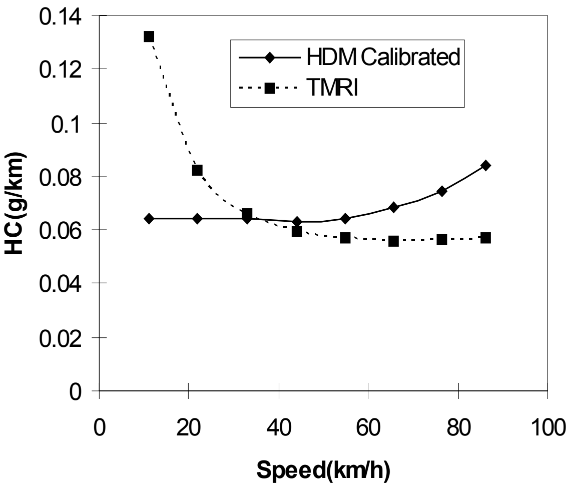


Figure 10 – HC emissions for medium car

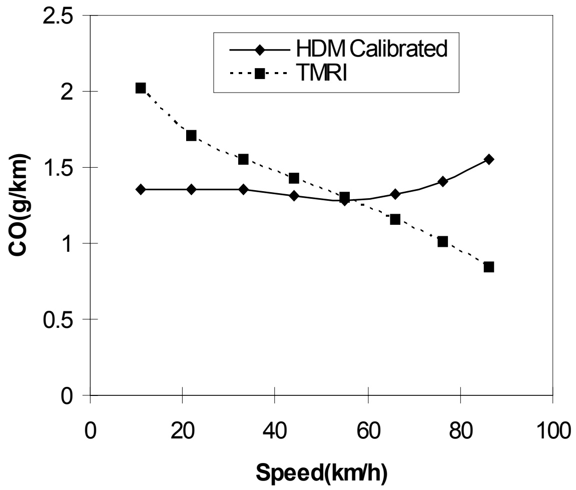


Figure 11 – CO emissions for medium car

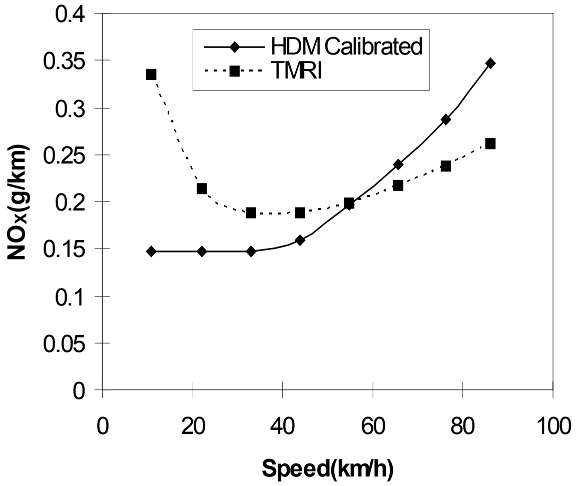


Figure 12 – $NO_X$ emissions for medium car

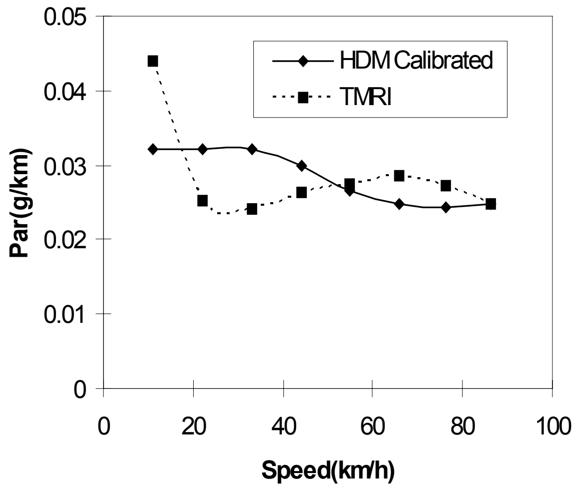


Figure 13 – Par emissions for medium car

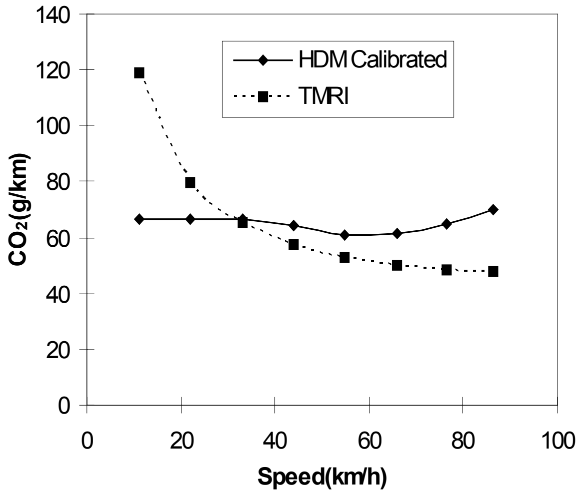


Figure 14 – $CO_2$ emissions for medium car

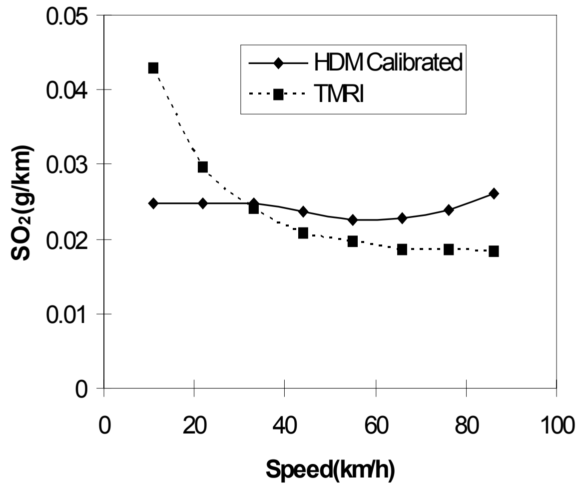


Figure 15 – $SO_2$ emissions for medium car

## 5. SUMMARY & CONCLUSIONS

This study presented the results of a basic calibration of the HDM-4 relationships for five types of Japanese vehicle. Moreover, it evaluated the transferability of HDM-4 RUE relationships to Japanese conditions by comparing HDM-4 outputs with earlier RUE studies in Japan. The HDM-4 RUE predictions using basic calibration data showed that most of the RUE relationships are robust and predictions may be improved through a more detailed calibration exercise. Thus, future work will focus on getting more reliable estimates for the parameters presented here and bridging the identified gaps, and on the calibration of speed and capacity relationships, fuel consumption, and tyre and lubricating oil relationships, which are not calibrated in this study.

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