

## EFFECT OF ROAD ROUGHNESS AND VEHICULAR SPEED ON EMISSIONS USING HDM-4

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### ABSTRACT

Almost every urban centre, not only in India, but throughout the world is facing the problem of poor air quality. Air pollution due to vehicle exhaust is a significant contributor to overall air pollution. Through tailpipe, vehicles emit various harmful chemical compounds as a direct result of combustion process. Since vehicular emissions are ground level sources, they have direct impact on health of human being. Traffic jams, long queues on signalized intersections and poor road conditions affect the steady pattern of flow which results into higher fuel consumption and consequently high vehicular emissions are observed. Savings in fuel consumption and curbing the related emissions is need of the present hour. Deteriorated roads results in higher fuel consumption and are responsible for higher emissions, therefore appropriate maintenance of roads is among the potential methods to reduce vehicles emissions.

In this study, a total of 5 alternatives including base case are created in the HDM- 4 software. Through base case, effect of road roughness and vehicular speed on emissions is estimated for vehicles cars and trucks. For cars, fuel consumption and emissions first increases, then decreases and finally increases on account of increase in roughness. This behavior of fuel consumption and emissions curve with respect to road roughness is explained in 3 zones. For trucks, fuel consumption and emissions always increases on account of increase in roughness. However rate of increase in fuel consumption and emissions is higher for higher values of roughness. Benefits of optimum maintenance and rehabilitation strategy for roads are evaluated in terms of savings in fuel consumption and reduction in vehicle emissions for the present study. Comparison of base case and optimum maintenance case for life term (20 years) yields savings of 4.4% in fuel consumption and 4.23% reductions in CO<sub>2</sub> emissions.

**Keywords:** vehicular emissions, HDM-4 software, rehabilitation strategy, economic evaluation

### 1. INTRODUCTION

India is second-largest country by population in the world. It has rapidly growing economy and transportation sector is a vital element. A sound transportation system not only offers greater personal mobility but also supports the industrial and commercial base of a country, facilitates the flows of external and internal trade and also allows for effective physical communications. Within developing countries like India transport infrastructure is often seen as the key to unlock economic growth.

On the other hand, because of this economic growth, the number of vehicles on Indian roads in the past has increased tremendously and this growth is expected to grow in the future also. This increase in number of vehicles is responsible for another set of problems including lack of space, reduction in natural resources, environmental pollution, etc. Vehicle emissions, in the form of conventional pollutants (CO, NO<sub>x</sub>, PM, HC etc...) and greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub> etc...), can have adverse impacts such as premature mortality, lower crop yields, environmental damage, and global warming. These problems, in turn, can set back the economy.

#### OVERVIEW OF EMISSION STANDARDS IN INDIA

Starting with Supreme Court of India interventions in the late 1980s, the country started moving towards mitigating the public health impacts of vehicle and fuel emissions. The initial steps consisted of eliminating lead in petrol, switching to compressed natural gas (CNG) for auto rickshaws and buses in Delhi and subsequently other cities, and establishing Euro 1/1-equivalent emission standards known as India-1 standards for new vehicles.

India has progressively lowered its permissible vehicular emission limits for new four-wheeler vehicles following the path laid by the European Union (EU). The Auto Fuel Policy of 2003 laid down a road map for vehicular emission and fuel quality standards. This road map has been largely implemented. In 2010, Bharat IV fuel quality standards and vehicle emission standards for four-wheeled vehicles were implemented in 13 major cities, while Bharat III standards took effect in the rest of the country.

Bharat Stage (BS) emissions standards are emissions standards instituted by the Government of India (GOI) that regulate the output of certain major air pollutants (such as hydrocarbons (HC), nitrogen oxides (NO), carbon

monoxide (CO), sulfur oxides (SO), particulate matter (PM) by vehicles and other equipment using internal combustion engines. They are equivalent to the European emissions standards. The National Fuel Policy commenced on October 6, 2003, is a phased program for implementing the EU emission standards in India by 2010. As of January 2013, Bharat IV standards had been expanded to about ten more cities. For two and three- wheelers, India followed an independent path and regulated emissions in a different manner than Europe and China. This first phase of emission reductions from all on- road vehicular sources shows great progress.

#### DESCRIPTION OF HDM-4

The Highway Development and Management (HDM) model, originally developed by the World Bank, is widely used as a planning and programming tool for the highway expenditure and maintenance activities. HDM-4 is a computer model that simulates physical and economic conditions over the period of the analysis for the series of alternative/alternatives and scenarios specified by the user. It is designed to make comparative cost estimates and economic evaluations of different construction and maintenance options.

#### Overview of HDM-4

The broad concept of HDM-4 is illustrated in Figure 1.1. The user defines a series of alternatives that describe different investment and preservation options for the road. The investments influence the condition of pavement over time and road maintenance costs. The pavement and traffic conditions have an influence on Road User Effects (RUE). The HDM-4 system predicts traffic speeds and the consumption of the RUE components, such as fuel, tyres etc. Multiplying these by the unit costs of the individual components gives the RUE over time. Comparing the cost outputs from various investment alternatives allows assessment of the relative merits, cost savings and benefits of the different alternatives using economic principles.

#### Analytical Framework of HDM-4

The HDM-4 analytical framework is based on the concept of pavement life cycle analysis. This is applied to predict the following over the life cycle of a road pavement, which is typically 15 to 40 years:

Road deterioration

Road work effects

Road user effects

- Socio-Economic and Environmental effects

HDM-4 simulates total life-cycle conditions and costs for an analysis period under a user specified scenario of circumstances. The primary cost set for the life- cycle analysis includes the costs to the road agency of maintaining and improving the road network and costs to road users of vehicle operation, passenger time and road accidents. Environmental effects in the form of vehicle emissions and energy consumption are quantified but not included in the cost streams. As illustrated in Table 1-2, HDM consists of a series of sub-models that address different aspects of the analysis. Each of these sub-models requires certain input data and each produces its own output.

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#### 1.3.3 Structure of HDM-4

The HDM-4 incorporates three dedicated applications tools for project level analysis, road work programming under constrained budgets, and for strategic planning of long term network performance and expenditure needs.

The three analysis tools (Strategy, Programme and Project) operate on data defined in one of four data managers:

• Vehicle Fleet

Vehicle Fleets are used to store details of the vehicle types to be included in HDM-4 analyses. A Vehicle Fleet consists of a number of vehicle types. Each vehicle type represents a category of vehicles in the traffic mix being modelled (e.g. small car, large truck, etc.). When creating a Vehicle Fleet, one should include 1 vehicle Type for each vehicle category in the traffic mix being modelled.

Road Network

An HDM-4 Road Network stores detail of the roads that one wish to analyse. Each Road Network consists of a number of sections.

Road Works

The Road Works folder provides facilities, within a flexible framework, to define a list of maintenance and improvement standards that are followed by road. organizations in their network management and development activities. New construction sections may also be defined.

HDM Configuration

Since HDM-4 will be used in a wide range of environments, HDM Configuration provides the facility to customise system operation to reflect the norms that are customary in the environment under study.

There are four sets of models in HDM-4 to carry out the technical analysis, the details of which are as follows:

Road Deterioration

Pavement deterioration manifests itself in various kinds of distresses, each of which is modelled separately in HDM-4. Road Deterioration models in HDM-4 predict pavement deterioration for bituminous, concrete and unsealed roads. The ideal maintenance treatment for a particular section of road will depend on the principal cause of distress.

Works Effects

When making a life-cycle cost analysis of a road, it is normally necessary to simulate in the modeling, the effects of various types of roadworks during the analysis period. These models simulate the effects of road works on pavement condition and determine the corresponding costs.

Road User Effects

Vehicle operating cost, road accidents and travel time are determined using these models.

Social and Environment Effects

Vehicle emissions, energy consumption and traffic noise analysis is undertaken using these models.

## 2. LITERATURE REVIEW

### GENERAL

When vehicle moves along a road, it encounters various forces which oppose the motion. The various resistances when the vehicle moves on the road are aerodynamic resistance, gradient resistance, rolling resistance, curvature resistance, inertial resistance which are as shown in Figure 2-1. Any change in road attributes that affect the forces opposing motion, will impact fuel consumption (as fuel consumption model in HDM-4 is related with forces opposing motion) and consequently vehicle emissions (vehicle emissions are related with fuel consumption by vehicles). The important attributes relating to the road are:

- Roughness
- Texture
- Gradient and • Curvature

Road Roughness is one such attribute, which affects forces opposing motion, therefore it indirectly affects fuel consumption and vehicle emissions. In actual roughness positively impacts on rolling resistance, therefore due to this resistance, fuel consumption and emissions are high on rough roads.

### EFFECT OF PAVEMENT ROUGHNESS ON VEHICULAR ROLLING RESISTANCE & FUEL CONSUMPTION

The rolling resistance is defined by Biggs as: "The total of all forces, apart from aerodynamic drag, acting on a freewheeling vehicle. Thus, it includes all frictional forces from the output of the gear box to the wheels and tyre resistance forces."

While many of the factors that affect rolling resistance are vehicle dependent. pavement properties play a small yet integral role in determining the overall rolling resistance a vehicle must overcome. Three pavement properties are believed to affect vehicular rolling resistance are pavement roughness (i.e. smoothness), surface texture and pavement stiffness.

Pavement roughness, describes the irregularities in pavement surface that adversely affect vehicle's ride quality and user costs. Roughness is normally quantified with the international roughness index (IRI) in most state agencies. Roughness has a significant effect on vehicle rolling resistance and fuel consumption. The following paragraphs chronologically summarize the findings of previous studies:

Study by White & Velinsky, in year 1979

White and Velinsky investigated the effect of road roughness on rolling resistance through field studies. A mechanistic pavement roughness model was developed based on field data collected. These models were applied to predict the vehicle energy losses from both the tire and suspension system. Sensitive analysis through the roughness model revealed that vehicle rolling losses increased with the increase of pavement roughness.

Study by Bester, in year 1984

Bester through experimental studies found the impact of pavement type and roughness on rolling resistance. He used an experimental method to measure the rolling resistance of passenger cars and trucks on eight different surfaces: asphalt, concrete, surface treatment, and unsurfaced. His study revealed that pavement type (asphalt vs. concrete) had only a small effect on rolling resistance. The roughness has an effect on the rolling resistance as smoother roads have lower rolling resistance values.

Study by Lucas & Laganier, in year 1990

Lu simulated the rolling resistance responses of a quarter car model with spectral density functions and investigated the influence of pavement roughness on the car rolling resistance. Results showed that the rolling resistance increased significantly with the increase of pavement roughness: pavement with bad surface condition may increase the vehicle rolling resistance by about 40%.

Lucas and Laganier evaluated the roughness effect on fuel consumption with three studies: laboratory studies, test track studies and open road studies. Pavement roughness was simulated with a vibration bench in the laboratory study. Results showed that roughness is an important factor for vehicle fuel consumption. Lucas et al plotted a graph between extra fuel consumption and unevenness level, the conclusion of which is-extra fuel consumption is ranging from 0 to 0.4 L per 100 Km for evenness rating from excellent to poor.

HDM-4 evaluates 'n' number of alternatives simultaneously in one analysis. Taking the advantage of this concept, total 5 alternatives including Base case are created for this study. Base case represents do-nothing or very little maintenance case. One more advantageous aspect of HDM-4 analysis is that, it does the life-cycle analysis. So, in the base case, road is getting deteriorated for the life term of pavement and the corresponding change in speed, fuel consumption and emissions is predicted by the software. In this way roughness and speed impact on emissions is analysed through base case outputs. Out of defined alternatives, one will be selected as optimum alternative based on economic indicators estimated by HDM-4. Then comparison between optimum alternative (economically and technical viable case) and base case will highlight the reductions in vehicle emissions and savings in fuel consumption when optimum alternative is opted.

Study by Sandberg, in year 1990

Sandberg conducted vehicle fuel economy studies on 20 different road surfaces that had different textures. These surfaces ranged from standard asphalt mixtures to chip seals and unpaved roads. Texture and roughness were measured using a laser profilometer attached to a passenger car. Sandberg concluded that fuel consumption could vary by 11 percent from the smoothest to roughest road.

Study by Delanne, in year 1994

Delanne through field experiments investigated the effect of pavement roughness on light vehicle fuel consumption. Ten different roadway sections were tested in France and vehicle rolling resistances were measured with hydraulic bench test. Test results showed that the increase of pavement roughness can increase the vehicle fuel consumption significantly: by up to 6%.

Study by Amos, in year 2006

Amos collected fuel data on a 22-mile interstate loop with a dump truck at 60mph. Data was collected before and after the pavement resurfacing. The IRI before and after resurfacing was 130 in/mile and 60 in/mile respectively. Results from fuel data showed that a 2.46% fuel saving was found for the dump truck before and after the roadway was resurfaced.

Study by Chatti & Zaabar, in year 2012

Five different vehicles were used in this study to assess fuel consumption relative to pavement type, vehicle speed, road roughness, and surface texture. Only flat and smooth pavement sections were used in order to determine the

direct effect of pavement surface texture and type on fuel consumption. Five different locations in Michigan were selected for testing with a medium car, SUV, van, light truck and (articulated) heavy truck. Fuel consumption was measured as testing was conducted in winter (wet conditions) and summer (dry conditions) and at three speeds (35, 45 and 55 mph). Five sections each of asphalt concrete (AC) and portland cement concrete (PCC) pavements were identified for testing, although it is not stated what type of PCC pavements (jointed plain concrete pavement, continuously reinforced concrete pavement, etc.) were included. Raw profile and texture data were collected by the Michigan Department of Transportation. The IRI on these pavements ranged between 0.8 and 6.0 m/km for AC pavements and 0.8 and 2.5 m/km for PCC pavements, while the texture ranged from 0.23 mm to 1.96 on the AC pavements and 0.23 to 2.7 mm on PCC pavements.

Using an analysis of covariance (ANCOVA), the authors estimated the effect of roughness on fuel consumption, as well as the effect of surface texture on fuel consumption. A regression and lack of fit analysis were conducted to determine the effect of surface texture on fuel consumption. The authors summarized that grade and IRI were each statistically significant and although surface texture was found to be statistically significant at 35 mph, it was not statistically significant at 45 and 55 mph.

**2.3 IMPLEMENTATION OF VEHICLE EMISSIONS ANALYSIS IN HDM-4-** The objective of modelling vehicle emissions is to assess the effects, in terms of pollutant quantities, of changes in road characteristics, traffic congestion, and vehicle technology. For each alternative and for each analysis year, the quantities of each component of exhaust emissions are computed separately for each vehicle type. The annual total quantities of emissions (by component) are obtained by summing over all the vehicle types. The following sections describe the inbuilt emission models in HDM-4.

**2.3.1 Basic Model Form-** The engine out emissions are estimated based on the fuel consumption rates, with CO: being calculated from Carbon balance assumptions. The engine out emissions are treated by the catalytic converter, if present, to yield the tailpipe emissions observed by the environment. The effectiveness of catalytic converters in reducing emissions is modelled through the term Catalyst Pass Fraction (CPF).

TPEEOE, CPF

TPE is tailpipe emissions which are actually observed by the environment.

EOE is engine out emissions which are actually produced during combustion process and then they are treated by catalytic converter (present in vehicle). CPF stands for catalyst pass fraction, which is effectiveness of catalytic converters in reducing emissions.

**2.3.2 Engine Out Emission Models-** These models give engine out emissions by component for standard motorised vehicle types. There are 16 standard vehicle types in HDM-4. The following components of vehicle exhaust emissions are modelled in HDM-4:

Carbon monoxide

Sulphur dioxide

Nitrous oxide

Hydrocarbons

Particulates

Lead

Carbon dioxide

**2.4 BRIEF OF FUEL CONSUMPTION MODEL IN HDM-4-** Mechanistic models predict that the fuel consumption of a vehicle is proportional to the forces acting on the vehicle. Thus, by quantifying the magnitude of the forces opposing motion one can establish the fuel consumption. Mechanistic models are an improvement over empirical models since they can allow for changes in the vehicle characteristics and are inherently more flexible when trying to apply the models to different conditions. Because of their numerous advantages over empirical models, mechanistic models were adopted in HDM-4.

One of the comprehensive mechanistic fuel consumption models available is the ARFCOM model, and its approach is summarised in Figure 2-3 and it is this ARFCOM model which is implemented in HDM-4. This shows how the total power requirements are based on the tractive forces, the power required to run accessories, and internal engine friction. The fuel consumption is then taken as proportional to the total power requirements.

### 3. SUMMARY OF FINDINGS

Smooth roads decrease vehicle fuel consumption and hence emissions. Every study that assessed the effect of unevenness or smoothness on pavement vehicle interaction showed that smoother pavements reduced rolling

resistance. The more is the smoothness, less is the rolling resistance. One such example of study that belongs to real world is Missouri rehabilitation project, which shows that reducing the IRI of a pavement from 130 to 60 in/mile (2.05 m/km to 0.95 m/km) could save 2.46 percent fuel. Currently, we understand that pavement roughness among the road characteristics has the greatest influence on rolling resistance. The effect of texture is smaller on well-maintained pavements, and no real study has been confirmed the effect of pavement stiffness on vehicular rolling resistance.

To accomplish presented research work, work is divided into different modules. The complete details of modules regarding how they are accomplished are as follows:

follows:

Module 1: Acquaintance to software HDM-4- The objective of this module was completed as training program titled "INTERNATIONAL COURSE ON DIISEMINATION OF HDM-4" organized by CENTRAL ROAD RESEARCH PROGRAM held during Sept. 2015 was attended.

Module 2: Related Literature Review

Comprehensive Literature review was done, which is already presented above.

Module 3: Creation of Project in HDM-4- For creation of project in HDM-4, data is stored in different folders of HDM-4, the details of which are shown in chapter 4.

Module 4: Running the software with inclusion of Emissions model While running the software, Emissions model was included.

#### 4. CONCLUSIONS

It was already stated earlier that roughness effects play a little role yet integrative while determining fuel consumption and emissions. Factors such as vehicle speed are having more sensitivity to fuel consumption and emissions. In this study, roughness is allowed to increase (in Base case), then due to increase in roughness, there is decrease in vehicle speed, both of which then are effecting fuel consumption and emissions. Roughness effects vary according to vehicle type. In this study, analysis of car and truck (3 axle truck) is carried out, conclusions of which are described below:

For Cars

- As the road deteriorates i.e. roughness increases, fuel consumption and emissions must increase, this seems quite obvious also but when roughness crosses a certain level, then there is significant change in roughness influenced speed and this decrease in speed plays a major role in determining fuel consumption than road roughness. That certain level is 5.5 IRI.

For trucks, roughness sensitivity to fuel consumption and emissions is higher than cars. There is 1 % increase in fuel consumption corresponding to increase in roughness of 1 IRI. These are exclusive roughness impacts because for initial values of IRI (less than 7 IRI), change in speed on account of increase in roughness is nil.

- Roughness sensitivity on CO<sub>2</sub> emissions is also 1%, these roughness effects can be seen before IRI of 7 because after this 7 IRI, there is significant change in speed on account of increase in roughness.

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