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Estimation of Air Pollution Cost for Optimization of Highway Alignment

Seyed Mahdi Sajjadi*, Mohd Zulkifli Bin Mohd Yunus, Othman Che Puan and Taha Mehmannavaz

Department of Civil Engineering, University Technology Malaysia, Johor, Malaysia

Abstract

The current air pollution increase prompts scientists to look for new candidates for highway alignment that would eventually result in reduced vehicle fuel consumption. In the current study, an empirical and computational method has been proposed which needs to be implemented simultaneously with the alignment optimization process so that different alignment candidates could be assessed in terms of fuel consumption of vehicles. The results obtained from the final equation indicate the total cost of CO2 clean-up required for each vehicle in each highway candidate and these costs could be compared to each other to determine the best candidate of highway.

Keywords: Air pollution; Cost estimation; Highway alignment; Mathematical and empirical modeling

Introduction

Deficiency of fossil fuel resources in the world and their growing demand has led to increased fuel prices all around the world. Thus, investigation of new methods to find candidates for highway alignment which will reduce the vehicle fuel consumption would be essential. Not only does reducing vehicle fuel consumption lead to reduced taxes within the society, but also it will result in reduced environmental pollution and threat to human health. Optimization methods developed for evaluation of alignment candidates in terms of minimizing the cost are addressed in the works of Trietsch [1], Fwa, Chan [2], Easa, Strauss [3], Jong and Schonfeld [4], Jha and Schonfeld [5], Schonfeld and Jong [6], Cheng and Lee [7], Lee, Tsou [8], Kang, Schonfeld [9], Kang, Yang [10], Kang, Jha [11]. Many optimization methods including linear programming, genetic algorithm, heuristics, dynamic programming along with mixed integer programming have been established to compute the optimal alignments required to plan a highway. The major decision making criterion hired in these models for optimization of highway alignments is the reduction of costs involved during the construction, which normally include the land acquisition costs, pavement costs, earthwork costs, etc. Therefore, this criterion does not consider the objectives imposed by other important stakeholders including the minimization of travel time by the road users, environmental costs and fuel consumption. An important decision making criterion to be considered within the process of highway alignment optimization is the fuel consumption rate as a result of selection of alignment candidates which could eventually reduce the fuel consumption rate for vehicles as an economical and desirable criterion. Many vehicular fuel consumption models [12-15] have been provided so far. One of the most important parameters that has affected the fuel consumption of vehicles is the highway geometry. The characteristics of highway geometrics like the horizontal curve radius, super elevation and grade are usually being employed to estimate the fuel consumed by the vehicle in a given highway. However, it should be noted that none of the above mentioned researches have considered such decision making criterion for determining and optimizing the process of highway alignment as reported.

There is a direct relationship between air pollution and fuel consumption. According to the World Health Organization (WHO), air pollution can be defined as [16]: "Air pollution is the contamination of outdoor and indoor environment by means of any chemical, biological and physical agent that modifies the atmospheric nature. Motor vehicles, household combustion devices, forest fires and industrial facilities are the most common sources of creating air pollution. The pollutants of public health concern include carbon monoxide, ozone, particulate matter, sulphur dioxide and nitrogen dioxide." Air pollution every year can impose significant financial losses and casualties to different countries all around the world. For example, according to the World Bank report in 2006 [17], approximately an eight-billion-dollar damage in the form of air pollution is being imposed on the Iranian government annually. In addition, every year according to the latest statistics provided by the Ministry of Health and Medical Education of Iran, nearly 3500 deaths occur directly due to air pollution. These financial losses and casualties also occur in other countries similar to Iran because this problem is global. In the current study, a useful mathematical model needs to be implemented along with the alignment optimization process so that different candidate alignments can be evaluated in terms of fuel consumption by the vehicle in addition to other costs. Hence, in the current study, a new empirical and mathematical equation has been provided which can determine the best candidate among several ones in terms of air pollution. This equation can act within the first phase of highway design of which there is not a lot of information related to highway candidates. So, the provided equation works with three effective parameters including length of each highway candidate segment, slope of each highway candidate segment and the difference between design speed and cruising speed. The results obtained by this equation can almost be conformed to real-world situations. Iran was the basis for conduction of this research that could be upgraded for other countries.

Greenhouse gases released by vehicles

Emissions produced by vehicles harmful to the environment are mostly related to fuel consumption levels. Such gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydro fluorocarbon (HFC), which are explained by EPA [18]. The main gas pollutant emitted by cars run on fossil fuels is carbon dioxide (CO_2), which produces 95% to 99% of this emission with different amounts once compared to the fuel type i.e. gasoline and diesel. The following values are being used by Environmental Protection Agency (EPA) and other agencies to determine the average carbon values in estimation of the CO_2 emission [19]:

CO_2 emitted from gasoline is equal to: 2347.7 gr CO_2/liter or 8,887 gr CO_2 / gallon.

*Corresponding author: Seyed Mahdi Sajjadi, Department of Civil Engineering, university Technology Malaysia, Johor, Malaysia, Tel: 6-07-5531581; E-mail: msseyed2@live.utm.my

CO_2 emitted from diesel is equal to: 2689.27 gr CO_2/liter or 10,180 gr CO_2 / gallon.

The above values highlight the CO_2 emissions from gasoline or diesel taken from international standards.

Determination of effective parameters on fuel consumption

According to different surveys conducted by the Iranian Department of Environment regarding the air pollution, it is expressed that about 70% of air pollutions are produced by passenger cars and motorcycles. The contribution of motorcycles and cars are 14.5% and 55.5% respectively. These statistics indicate that for determination of the optimal candidate of highways, the effects of fuel consumption along with the air pollution produced by vehicles should be considered. This means that if the selected candidate is capable of reducing the vehicle fuel consumption, this candidate could also minimize the air pollution cost, in respect to the concept that fuel consumption and air pollution are totally related to each other. The main causes of air pollution from vehicles can be divided into three categories including vehicle fuel quality, quality of vehicles and the amount of fuel consumed by vehicles. In this study, it has been assumed that the vehicle fuel quality and quality of vehicles are in an international standard condition as well as are identical among all candidates. The amount of fuel consumed by vehicles is directly related to the amount of force produced by the vehicle and this force is used for moving the vehicle into various environmental conditions (e.g., amount and direction of wind) and the highway geometric (e.g. road longitudinal slope) according to the findings of Kang, Shariat [15]. In this study, the effective factors on the amount of fuel consumed by vehicles along the inter-city highways are divided into two general categories including:

α. Factors related to technical specifications and type of vehicle including: cruising speed, engine type, type of tires, tire air content, consumable filters type for air and oil, type of engine oil, vehicle weight, etc.

β. Factors related to the geometrical characteristics of the candidate including: design speed, maximum slope, length of candidate, etc. [20].

Moreover, the cost of vehicle operation is significantly affected by the fuel consumption. Fuel consumption also influences the emission of various pollutants and greenhouse gases especially when fossil fuels are being used. Consequently, to distinguish fuel efficiency and eco-friendly highways, it is important to evaluate the effect of highway geometry on fuel consumption of the vehicle. Boriboonsomsin and Barth [14] have highlighted in their real world experiment that fuel economy of light-duty vehicles can be verified by means of road slope and this certainly proved to have significant affects. Also, the total length of roadway segments with varying slopes in the standard pavement surface roughness has been accounted for fuel consumption of vehicles. Considering all the above mentioned factors for fuel consumption, a fuel consumption equation, sensitive to highway geometry, for vehicles has been developed in this study. Although the factor (a) mentioned above is approximately fixed for all the candidates, the factor (b) can be different for each of the highway candidates. For instance, regarding the cruising speed for technical specification of vehicles, the maximum speed (cruising speed) produced for most of the passenger vehicles used in Iran in terms of optimized fuel consumption rate is 95 to 100 kilometers per hour.

Based on field studies for the current research, it has been found that a one-kilometer increase per hour to cruising speed of vehicles with high frequencies within the case study region (Iran) until the design speed of the highway, a one-percent increase in fuel consumption of the vehicles was observed. This indicates that increasing the speed more than 100 km per hour (cruising speed in Iran) in standard conditions in terms of alignment, geometric and environmental conditions would increase the fuel consumption by one percent for each one km per hour (in case study region). This cruising speed is different for varying models of vehicles being considered. Besides, design speed means that the highway alignment has been designed for this speed and violation of this speed will lead to reduced highway safety. Thus, if the design speed for a highway alignment is for example 110 kilometers per hour, this means that it is 10 kilometers per hour more than the cruising speed for the case study region. Another important parameter in vehicle fuel consumption being considered in this study is highway candidate slope. Boriboonsomsin and Barth [14] have expressed that by increasing the highway candidate slope, fuel consumption will be increased to about 15% to 20%. The last parameter effective on fuel consumption rate considered in this study is distance traveled by the vehicle. This means that the longer the distance travelled by the vehicle, the higher its fuel consumption. Therefore, it can be inferred that fuel consumed by vehicles is a function of the difference between the design speed and cruising speed, slopes of highway candidate segments and lengths of highway candidate segments which could be summarized in the following empirical equation:

$$F_C = f(V, L) + f(S, L) \tag{1}$$

Where

F_C = total consumed fuel by each vehicle and for each candidate (liter)

V = the difference between the design speed and cruising speed

L = candidate length

S = longitudinal slope of the candidate

Therefore, the main objective of this study is to obtain the amount of fuel consumption by each vehicle in the defined highway candidates based on the difference between design speed and cruising speed, slopes of highway candidate segments and lengths of highway candidate segments. According to the Regulations Geometric Design of Iran Roads [21], the maximum longitudinal slope for freeways, highways and main roads are listed in Table 1.

The maximum allowable slope based on Regulations Geometric Design of Iran Roads [21] (Table 1) is 6%. A field study within the case study region related to fuel consumption and slope of highway candidate showed that by increasing each 1 percent to the longitudinal slope, the fuel consumption increased around 2.5% till maximum allowable slope for highways in standard conditions. This finding is in agreement with the results of studies of Boriboonsomsin and Barth [14]. Table 2 highlights the results of this field study for maximum allowable slope.

According to the above information, the following function can be incorporated to calculate the amount of fuel consumption along the highway candidate:

$$F_c \in \sum \{S_f \alpha V_{ai} L_i, S_f \beta S_i L_i, S_f L_i\} \tag{2}$$

Eqn. (3) is the final function which could count the total amount of fuel consumed by each vehicle and each highway candidate comprehensively:

$$F_C = S_f \times \left[\sum_{i=1}^{nos} á \times V_{ai} \times L_i + \sum_{i=1}^{nos} â \times S_i \times L_i \right] + S_f \times L_i \tag{3}$$

Where

F_C = the total fuel consumed by each vehicle and each candidate (liter)

Region Type			Design Speed (kmph)			
	80	90	100	110	120	130
			Maximum Longitudinal Slope			
Smooth	4	4	4	3	3	3
Hill	5	5	5	4	4	-
Mountain	6	6	6	6	-	-

Table 1: Maximum longitudinal slope for freeways, highways and main roads.

Additional Longitudinal Slope (%)	0	1	2	3	4	5	6
Additional Fuel Consumption (%)	0	2.5	5	7.5	10	12.5	15

Table 2: The relationship between the road longitudinal slope and fuel consumption.

S_f = optimal fuel consumption per kilometer in cruising speed for vehicles with high frequencies that will cross the highway candidate

$V_{ai} = V_{i(design)} - V_{i(cruising)}$ (If $V_{i(design)} \leq V_{i(cruising)}$, then V_{ai} will be equal to zero because the maximum allowable speed in each highway candidate is equal to the design speed of the highway candidate) $\left(\frac{liter}{Km}\right)$

L_i = length of ith segment of alignment (km)

S_i = slope of ith segment of alignment (%) (If $S_i \leq 0$, then no will be equal to zero)

nos = total number of different alignment segments

α = coefficient of increased fuel consumption by adding speed on the cruise speed for the case study region (this coefficient for vehicles used in Iran is equal to 0.01 while for other study area can be different even can be as a function)

β = coefficient of increased fuel consumption by adding slope till allowable slope (this coefficient for vehicles used in Iran is 0.025 which was explained in Table 2 while for other study area can be different even can be as a function)

S_f, for each vehicle is a certain amount. For example, the average value of S_f in Iran is usually equal to 0.08 liter per kilometer, or it can be expressed that the optimized fuel consumption in cruising speed and standard conditions for most vehicles in Iran is equal to 0.08 liter per kilometer.

Amount and cost of air pollution

The most common fuel consumed by vehicles in Iran is gasoline. Eqns. (4), (5) and (6) obtained from the descriptions of previous sections can calculate the amount and costs related to air pollution for gasoline or diesel fuels in intercity highway candidates. These equations consider the impact of carbon dioxide only:

$$A_{p(gasoline)} = 2.3477 \times F_C \tag{4}$$

$$A_{p(diesel)} = 2.6893 \times F_C \tag{5}$$

$$C_{Ap} = A_p \times upc \tag{6}$$

Where

2.3477 is the amount of CO_2 emitted from gasoline (Kg) for each litter of fuel consumption (This amount is explained in section 2 of current paper)

2.6893 is the amount of CO_2 emitted from diesel (Kg) for each litter of fuel consumption (This amount is explained in section 2 of current paper)

$A_{p(gasoline)}$ = total amount of air pollution due to CO_2 (Kg) from gasoline $A_{p(diesel)}$ = total amount of air pollution due to CO_2 (Kg) from diesel

C_{Ap} = total cost of CO_2 clean-up for each vehicle and each candidate ($)

upc = unit cost of CO_2 clean-up ($/kg) According to Ardekani and Sumitsawan [22], the average unit cost of CO_2 clean-up is about 18 $ / metric ton or 0.018 $ / kg.

Model limitations

This equation is an empirical function which has a good relationship with fuel consumption in the real world. There are three limitations in this equation that should be solved in future studies listed as follows:

In each highway candidate, there may have been several segments with different slopes. Some of these segments in one direction have positive slope and some negative slope and in the opposite direction which indicates that the slopes are reversed. This equation is applicable to positive slopes while in candidate segments with a negative slope, it should be considered zero or in other words, in candidate segments with a negative slope, S_i will be equal to zero.

In this equation, it is assumed that the cruising speed should be less than design speed. Thus, V_{ai} in Eqn. (3) has always a positive sign. If $V_{i(design)} \leq V_{i(cruising)}$, then V_{ai} should be considered zero because the maximum allowable speed in highways is equivalent with the design speed of highways and violation of design speed will lead to reduction of highway safety.

This model is used to determine fuel costs for each candidate of highway in planning stage and regarding the planning stage, there is no accurate information from each candidate; therefore, this model does not consider all the parameters related to fuel consumption including temperature, superelevation, pavement roughness, wind blowing and etc. This equation is also provided only for vehicles with high frequencies that may cross the highway candidates in future.

Example

An example has been provided here to demonstrate how to work with the proposed equation along with validation of this equation with a real world case study. In this example, two highway candidates are defined between two points based on some constraint parameters. The geometric specifications of this case study are shown in the Tables 3-5. The horizontal alignment and vertical profile of these two candidates are shown in Figure 1. The final target of this example is to determine the best candidate in terms of air pollution cost. In this example is assumed that the suggested AADT is for both directions of candidates (50% of AADT for direction from origin to destination and 50% for direction from destination to origin of candidates). The results obtained from Eqns. 3 to 5 are shown in Tables 6 and 7 for Alignment-1

Roadway Candidate Parameters
Design Speed = 110 $\frac{Km}{h}$
AADT = 2000 $\frac{veh}{day}$
Vehicle parameters
Cruising Speed =100 $\frac{Km}{h}$
S_f= 0.08 $\left(\frac{lite}{Km}\right)$
α= 0.01
β =0.025
Unit Cost of CO_2 Clean-up = 0.018 $(\$/kg)$

Table 3: Geometric specifications and other parameters used in the example.

nos	L_i (Km)	S_i (%)	V_{ai}
1	0.02972	-0.43	10
2	0.10376	2.56	10
3	0.06238	-1.45	10
4	0.08594	2.95	10
5	0.10865	1.64	10
Total	0.39045		

Table 4: Specifications of the alignment-1.

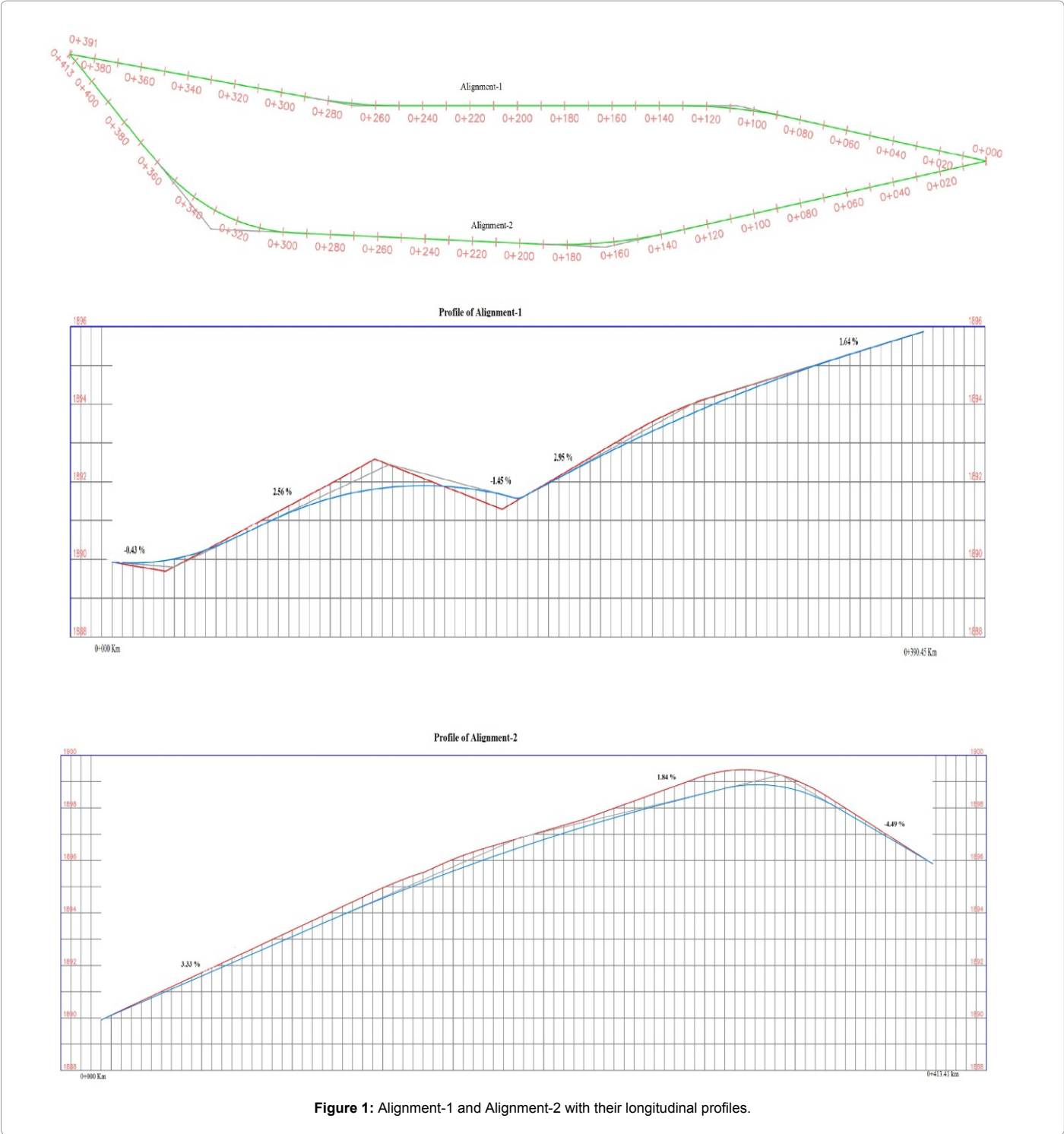| nos	L_i (Km)	S_i (%)	V_{ai}
1	0.20832	3.33	10
2	0.130	1.84	10
3	0.07509	-4.49	10
Total	0.41341		

Table 5: Specifications of the alignment-2.

Figure 1: Alignment-1 and Alignment-2 with their longitudinal profiles.

From Origin to Destination for AADT 1000 (Veh/day)						
nos	L_i Km	F_c Liter	A_p (gasoline) Kg	C_{ap} $	C_{ap} for AADT for One Side of the Road for 1000 (Veh/day) $	Total C_{ap} for One Year based on One way of the road $
Total	0.39045	0.0357542	0.083940	0.001511	1.51092536	551.4877566
From Destination to Origin for AADT 1000 (Veh/day)						
nos	L_i Km	F_c Liter	A_p (gasoline) Kg	C_{ap} $	C_{ap} for AADT for One Side of the Road for 1000 (Veh/day) $	Total C_{ap} for One year based on One Way of the Road $
Total	0.39045	0.0345660	0.081151	0.001461	1.460713354	533.1603741
Total Cost of Air pollution for Alignment-1 in One Year =1084.65 $						

Table 6: The results obtained from Eqns. 3 to 5 for Alignment-1.

From Origin to Destination for AADT 1000 (Veh/day)						
nos	L_i Km	F_c Liter	A_p (gasoline) Kg	C_{ap} $	C_{ap} for AADT for One Side of the Road for 1000 (Veh/day) $	Total C_{ap} for One Year based on One way of the road $
Total	0.41341	0.0382458	0.089790	0.001616	1.616217818	589.9195035
From Destination to Origin for AADT 1000 (Veh/day)						
nos	L_i Km	F_c liter	A_p (gasoline) Kg	C_{ap} $	C_{ap} for AADT for One Side of the Road for 1000 (Veh/day) $	Total C_{ap} for One year based on One Way of the Road $
Total	0.41341	0.0370543	0.086993	0.001566	1.565866569	571.5412978
Total Cost of Air pollution for Alignment-2 in One Year = 1161.46 $						

Table 7: The results obtained from Eqns. 3 to 5 for Alignment-2.

and Alignment-2 respectively. As can be observed from Tables 6 and 7, it can be inferred that the total cost of air pollution in Alignment-1 and Alignment-2 are 1084.65 $ and 1161.46 $ respectively. According to the objective of this paper, it can be understood that the Alignment-1 would be the best candidate for air pollution cost because it imposes the least air pollution costs relative to Alignment-2. Therefore, this equation can be incorporated among several highway candidates for determining the best candidate in terms of air pollution costs in planning stage of the highway design.

Conclusions

In this study, an attempt has been made to develop a mathematical and empirical equation to determine the cost of CO_2 clean-up in each highway candidate. This equation can be hired in determination of the best candidate for highways in terms of air pollution during the planning stage. The fuel consumption equation provided in this research is based on length, slope and the difference between the design speed and cruising speed. These three parameters can be found in planning stage of highway optimization. Thus, this equation could contribute to determination of the best candidate of highway alignment through rapid provision of fuel consumption by vehicles. The results of this study along with the provided example highlight a significant cost for CO_2 clean-up from the environment in a year for each defined alignment. Therefore, selecting the best candidate for highway in terms of fuel consumption could decrease the air pollution within the environment. This equation has been proposed for Iran's environment but could also be upgraded to other territories throughout the world.

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