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# Determining optimal speed limits in traffic networks

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ABSTRACT

Determining the speed limit of road transport systems has a significant role in the speed management of vehicles. In most cases, setting a speed limit is considered as a trade-off between reducing travel time on one hand and reducing road accidents on the other, and the two factors of vehicle fuel consumption and emission rate of air pollutants have been neglected. This paper aims to evaluate optimal speed limits in traffic networks in a way that economized societal costs are incurred. In this study, experimental and field data as well as data from simulations are used to determine how speed is related to the emission of pollutants, fuel consumption, travel time, and the number of accidents. This paper also proposes a simple model to calculate the societal costs of travel and relate them to speed. As a case study, using emission test results on cars manufactured domestically and by simulating the suburban traffic flow by Aimsun software, the total societal costs of the Shiraz-Marvdasht motorway, which is one of the most traversed routes in Iran, have been estimated. The results of the study show that from a societal perspective, the optimal speed would be 73 km/h, and from a road user perspective, it would be 82 km/h (in 2011, the average speed of the passing vehicles on that motorway was 82 km/h). The experiments in this paper were run on three different vehicles with different types of fuel. In a comparative study, the results show that the calculated speed limit is lower than the optimal speed limits in Sweden, Norway, and Australia.

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## 1. Introduction

One scheme to control the societal cost of travel in traffic systems is to set speed limits based on the notion of optimal speed with respect to societal costs. Milliken et al. [1] mention four primary approaches to setting speed limits: statuary limits, optimal speed limits, engineering study method with speed limits set near the 85th percentile speed, and an expert system-based approach. Elvik [2] points out that "an optimal speed limit is set to minimize the total costs to society of transport." In other words, determining optimal speeds and correct reinforcement of speed limits in traffic systems will result in minimizing the unwanted costs of travel such as accidents and the emission of pollutants. Cameron [3] has shown that "rationalisation of speed limits applicable to each class of rural road and for each type of vehicle, making the limits consistent with the optimum speed in each case, has the potential to reduce casualty crashes and crash costs substantially."

There are many factors involved in determining optimal speeds, including travel time, number of accidents, creation of environmental pollutants, and fuel consumption. One can also consider the effect of speed on road maintenance and highway erosion costs, but the societal costs of these are small in comparison with the total societal costs—less than 5 percent based on cost estimates from Sweden and Norway [2]—and hence, can be neglected. In the present work, factors such as accidents, travel time, environmental pollutants, and fuel consumption have been considered.

In this paper, estimates available from national organizations have been taken as the best estimates for the cost of accidents and the value of time in society. The rate of pollutant emission and fuel consumption at different speeds have been estimated using laboratory work and by random sampling from cars manufactured domestically and burning three different types of fuel, namely, natural gas, petrol, and diesel.

According to Milliken et al. [1], Keuken et al. [4], and Baldasano et al. [5], in some cases, speed limits have been determined based on societal cost; for example, "in 1995, Congress repealed the national maximum speed limit (NMSL) of 55 mph (89 km/h), returning to the states the responsibility for setting speed limits on major highways" [1], or "a speed limit of 80 km/h with 'strict enforcement' has been introduced in 2005 on zones of urban motorways in the Netherlands with the aim to improve air quality of $NO_2$ and $PM_{10}$ along these motorways" [4], or

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"the measure of speed limitation (80 km $h^{-1}$) is applied to the access roads of the Barcelona Metropolitan Area, formed by Barcelona and 19 other municipalities, with high levels of $NO_x$ and $PM_{10}$ emissions" [5, 6]. In such cases where the speed planner tries to determine the speed limits on the basis of one specific parameter, it will be purely accidental if the selected speed should also be optimal with respect to societal costs. Crouch [7] makes similar remarks in a research on the National Maximum Speed Limit. It is recommended that in such cases the societal costs of a plan be considered separately and the plan be economically justified.

This paper proposes a simple model to calculate the societal costs of travel and its relation to speed. In order to apply this model, first the relationship between speed and fuel consumption, pollutant emission, number of road accidents, and travel time must be determined. Then, a reasonable evaluation of all of the considered parameters must be determined. Following that, the optimal speed can be determined based on the model obtained in this study. In Section 3, the role of optimal speed and its relationship with speed limit and design speed is elaborated. In Section 4, the case study is introduced and analysed, and in Section 5, the results are compared with Norway, Sweden, and Australia. In this study, the total societal costs of the Shiraz-Marvdasht motorway have been estimated by using emission test results on cars manufactured domestically and simulating the suburban traffic flow. Finally, the results of the study are presented in the Conclusion of the paper.

For the case study, it was assumed that the vehicles are in a standard driving cycle test setting [8,9]. In addition, based on the requirements of the present research, only samples with constant speed (zero acceleration) and in hybrid cycle were considered and samples in cold start emission condition were omitted. The test was carried out without considering the effect of slope.

## 2. Model

Numerous factors affect the travel cost of a moving vehicle, not all of which are related to speed. When societal costs are not dependent on speed or if their effects are negligible, they can be ignored in the calculation of optimal speed and be represented by a constant ($C$) as shown in Eq. (1). This equation is used for calculating the total societal cost of travel. Here, E(AC), E(TTC), E(CFC), and E(EC) denote the total societal costs of accidents, travel time, fuel consumption, and pollutant emission, respectively.

$$\text{Total cost} = k_1 \times E(\text{AC}) + k_2 \times E(\text{TTC}) + k_3 \times E(\text{CFC}) + k_4 \times E(\text{EC}) + C \tag{1}$$

where $C$ is the constant term, the societal cost of travel that is independent of speed.

Eq. (1) is an extension of Crouch's equation in calculating travel costs [7]. In this equation, the factors that affect safety and have a significant societal cost such as the factors of road accidents, travel time, environmental pollutants, and fuel consumption have been used for determining the societal cost of travel. The weighting coefficients $k_1$, $k_2$, $k_3$, and $k_4$ are set based on the relative importance of the factors. Some level of accidents, travel time, fuel consumption, and pollution has to be accepted. A value of *zero* for a coefficient would mean ignoring the effect of its respective factor. Setting all of the coefficients to 1 would mean assigning equal importance to all of the factors. In this paper, the road user perspective and the societal perspective based on Elvik's [2] weighting have been considered. In Table 1, Elvik [2] has proposed coefficients for the different factors in determining the optimal speed limit. Eq. (1) calculates the total cost from a societal perspective. This is in contrast with "the road user perspective, which includes those costs that the road user pays out of pocket or those that can reasonably be assumed to be completely internalized by the road user in his or her choice of speed" [2]. The optimal speed can be calculated by setting the derivative of the total cost with respect to speed equal to zero as shown in Eq. (2). It can also obtained by drawing the graph of total cost versus speed.

$$\frac{d(\text{Total cost})}{dV} = 0 \tag{2}$$

in which $V$ denotes the speed.

### 2.1. Relation between speed and societal cost of fuel consumption

The rate of fuel consumption of a vehicle is a function of speed and it is measured in units of fuel per unit distance traveled:

$$\text{Fuel consumption} = F_f(V) \tag{3}$$

where the index $f$ denotes the type of fuel. If the average distance traversed by vehicles is denoted by $d$, then the total societal cost of fuel consumption, $E$(CFC), resulting from these vehicles moving on the road is given by:

$$E(\text{CFC}) = \sum_{f=1}^{n} \left( F_f(V) * W_f * d * n_f \right) \tag{4}$$

in which $n_f$ denotes the number of vehicles consuming a fuel of type, $f$ and $W_f$ is the unit fuel consumption cost measured in monetary units per unit of fuel, and $n$ is the number of fuel types available.

### 2.2. Relation between speed and societal cost of pollutant emission

Although the most important effect of pollutant is on people's health and is seen mainly in big cities, environmental pollutants are also important in suburban routes. They adversely affect agricultural produce and zoological and herbal ecosystems, and cause low visibility, global warming, and damage to historical monuments and landmarks [10,11]. It is known that pollutant emission rate is a function of speed [12]. If a vehicle produces the pollutant $p$, the emission rate of the pollutant can be calculated using the following function:

$$\text{Emission function} = H_{fp}(V) \tag{5}$$

where $f$ denotes the fuel type. $H_{fp}(V)$ is measured in units of mass of the pollutant per unit distance traversed by the vehicle. The total societal cost of pollutant emission can be calculated as follows:

$$E(\text{EC}) = \sum_{f=1}^{n} \left( \sum_{p=1}^{x} \left( H_{fp}(V) * W_p * d * n_{fp} \right) \right) \tag{6}$$

where $n$ and $n_p$ are the number of studied fuel types and pollutant types, respectively, $n_{fp}$ denotes the number of vehicles on the route which use the fuel type $f$ and produce the pollutant type $p$, $W_p$ is the emission cost in monetary units per unit of mass of the pollutant $p$, and $d$ is the average distance traversed by the vehicles on the route.

**Table 1**
Alternative perspectives in determining the optimal speed limit [2].

| Type of impact | Societal perspective | Road user perspective |
|---|---|---|
| **Travel time** | 100% | 100% |
| **Vehicle operation costs** | 100% | 100% |
| **Road accident costs** | 100% | 60% Norway/70% Sweden |
| **Environmental costs** | 100% | 0% |

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