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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.

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%

2.3. Relation between speed and societal cost of accidents

Elvik [13] points out that "there is a strong statistical relationship between speed and road safety." Nilsson [14], a Swedish researcher, proposed the power model to describe the effect of speed on road safety. "While Nilsson's model appears satisfactory for rural highways and freeways, the model does not appear to be directly applicable to traffic speed changes on urban arterial roads" [15]. In Elvik [16,17], a re-analysis of Nilsson's power model is made and a new set of exponents are suggested for it.

To simplify the calculation of the societal costs of accidents, we divide accidents into four categories: fatal accidents (fa), accidents resulting in injuries (ia), damage (da), and no financial or physical costs (na).

$$\begin{aligned} E(\mathrm{AC}) = \Bigg(& \left(\left(\frac{V}{V_{\text{before}}}\right)^{\text{exponent }_1} \text{fatal accidents}_{\text{before}}\right) * W_{\text{fa}} \\ & + \left(\left(\frac{V}{V_{\text{before}}}\right)^{\text{exponent}_2} \text{Injured accidents}_{\text{before}}\right) * W_{\text{ia}} \\ & + \left(\left(\frac{V}{V_{\text{before}}}\right)^{\text{exponent }_3} \text{PDO accidents}_{\text{before}}\right) * W_{\text{da}} \Bigg) \end{aligned} \tag{7}$$

where W_{fa}, W_{ia}, and W_{da} are the costs of fatal accidents, accidents resulting in injuries, and injuries resulting in damage, respectively, and V denotes average traffic speed. What is meant by the word "before" here is the values observed before the change in average traffic speed.

Any function in which a variable is raised to a certain exponent is called a power function [13]. The exponents in each part of the formula need to be estimated using statistical studies.

2.4. Relation between speed and societal cost of travel time

It is obvious that travel time is a function of speed. If $T(V)$ denotes the travel time of a vehicle traveling on a road under study, it is measured in units of time per unit distance traversed by the vehicle.

The total societal cost of travel time, $E(\mathrm{TTC})$, can be calculated as follows:

$$E(\mathrm{TTC}) = \sum_{j=1}^{n} U * \mathrm{T}(V) * d * x \tag{8}$$

where n is the number of the vehicles traveling on the road, d is the distance traveled, and x is the number of the passengers in the vehicle. U denotes the average value of passengers' time in monetary units per unit of time.

3. Relationship between optimal speed and maximum speed limit

The operational speed method is one of the methods of determining speed limits based on drivers' experience; it assumes that drivers are able to determine the appropriate speed. In the method of optimal speed limit, the speed limit is determined based on the drivers' performance as well as accident severity—such as property damage only, injury, and fatality—without taking the assumption that drivers may be capable of determining their appropriate speed. The optimal speed method is based on societal cost and benefit analysis. This method has not been very popular among traffic experts, although it is based on public well-being. If the optimal speed is determined correctly and all of the relevant factors are considered in deriving it, a question will be raised whether it is possible to consider it as the maximum speed limit. If considered honestly, the answer to this question will be negative because drivers' should be entitled to trade off more cost for higher speeds in emergency situations. Also, their right to drive and select the speed with the lowest societal cost considering others' rights should be recognized. It can be concluded then that speed limits should always be higher than or on average equal to the optimal speed. Besides this, there are other reasons for setting a speed limit that is higher than the optimal speed; for example, there are always cautious drivers who select speeds much lower than the speed limit for their travels. Assuming that no vehicle crosses the speed limit (as is the purpose of setting a speed limit) the average speed of passing vehicles will be less than the optimal speed. This will go against the optimal speed theory as a result of the increase in societal cost because of the decrease in average speed.

A more appropriate way to use the optimal speed is to consider it as the minimum speed limit and to apply other methods for determining speed limits. To highlight the importance of this issue, consider a situation in which, in the experimental group, the drivers' characteristic of caution results in choosing a lower speed; in this case, the use of available experimental methods such as setting speed limits near the 85th percentile speed or the operational speed method will lead to a violation of the societal rights of the people who actually select the optimal speed. By considering the optimal speed to be the minimum allowable speed, this concern will be removed.

Another concern is that the road might not have enough capacity for all the traffic to move at the optimal speed, thereby forcing drivers to select a speed which is lower than the optimal speed. Under such circumstances, this incorrect selection of speed will result in high social costs to be incurred and will cause the whole plan to fail.

It should be noted that in order for higher efficiency to be achieved, the optimal speed should be applied in a way that it corresponds to the statistical mode of speeds selected by drivers. Hence, the optimal speed should always be lower than or equal to the maximum speed limit and the maximum speed limit should naturally be lower than or equal the design speed to address the concern mentioned above. Eq. (9) describes these relations:

$$\text{optimal speed} \leq \text{maximum speed limit} \leq \text{design speed} \tag{9}$$

4. Analysis and design of case study

The Shiraz-Marvdasht motorway is one of the busiest routes in Iran. It contains three passing lanes on each side, which are separated using a median barrier. Interchanges are also used on this route; in other words, there is no other way to cross it.

As the Iranian transportation fleet is specific to the country, the figures for pollutant emission and fuel consumption are based on experimental surveys on public vehicles of this system. The vehicles undergo tests in the 273.2 k and 101.33 kpa (2012) situations. Detailed dates of the experimental situations are included in the E/ECE/324 report from the United Nations [8,9].

The average travel time of vehicles largely depends on the dynamics of traffic flow. The average times of traffic flow at different speeds have been estimated using real traffic flow data as well as simulation using the Aimsun software.

The results indicate that the change in the average travel times of the total traffic flow with a change of speed limits from 90 km/h to 120 km/h is approximately 6.41 sec/km. Meanwhile, the change in the average travel times of the total traffic flow is approximately 18.8 sec/km with a change of speed limits from 60 km/h to 90 km/h. Comparisons of these results show that the change is more significant in lower speed limits than in higher speed limits. That is to say, changes in speed limits have a greater effect on average travel times of the total traffic flow in low-speed routes than in high-speed routes [18]. According to Aljanahi et al. [19], "the main benefit of high-speed traffic flow is that the cost attributed to travel time is reduced," but here, the benefit is seen more in traffic flows with lower speeds. For example, as illustrated in Fig. 1, by increasing the speed from 20 to 40 km/h, $19.5 million will be gained in societal cost of travel time, while an increase of speed from 100 to 120 km/h will only result in a gain of only $0.59 million.

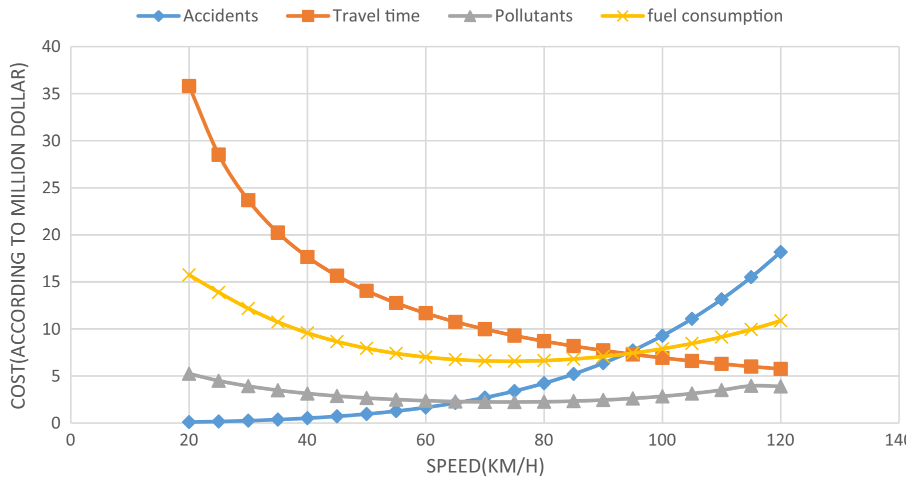

Fig. 1. Societal costs of traveling in different speeds.

The total societal cost includes travel time, the cost of accidents, the cost of pollutants, and the cost of fuel consumption in a year; the total societal cost versus speed limit is presented in Fig. 1, which shows that at lower speeds, the cost of travel time is higher than the other costs, but at higher speeds, it is the lowest societal cost while the cost of accidents is the highest. If the minimum cost of accidents is sought, the optimal speed will be equal to the lowest available speed. On the other hand, if the minimum cost of travel times is to be obtained, the optimal speed will be the highest available speed. The optimal speed based on the societal costs of pollutant emission and fuel consumption will be 74 km/h. The calculated optimal speeds are presented in Table 2, in which speed (V) is in km/h and y is the societal cost in US dollars. In Table 2, e is the natural exponential function and E means (*10^).

In Table 2, Eq. (7) has been used for estimating the societal cost of accidents. The road accident data was collected by referring to the information made available by the traffic police. In rural roads, the average cost is $1229.1 for property damage only, $51,487 for injury accident, and $1,945,080 for fatal accidents [20]. In Table 2, the societal cost of travel time has been estimated using real-world traffic data for various speeds and the average value of lost time per hour is equal to $0.2546 [20]. The societal cost of pollutants has been calculated using the figures published by the World Bank [21] combined with the results of emission tests on three common types of passing vehicles with diesel, gasoline, and double (gasoline + CNG) fuel at different speeds using Eq. (6). The emission tests data was collected by referring to the information made available by Iran Standard & Quality Inspection Co. for carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x), and carbon dioxide (CO_2). The societal cost of fuel consumption was obtained using the carbon balance method [22] by applying Eq. (4) to the results of tests on the statistical samples. Aggregating the above costs using Eq. (1) with $k_1, k_2, k_3, k_4 = 1$ and $C = 0$ [2] yields the estimated cost from a societal perspective.

R^2 values of pollutant emission for gasoline, diesel, and double (in CNG mode) vehicles are 0.444, 0.462, and 0.498, respectively. Similarly, R^2 values of fuel consumption for gasoline, diesel, and double vehicles are 0.593, 0.634, and 0.477, respectively. R^2 value of societal cost of travel time is equal to 0.976.

Fig. 2 presents speed limits in a one-year period for all passing vehicles from the societal and road user perspectives. From the road user perspective, the cost of pollutants is ignored and the cost of accidents is regarded to consist of vehicle damage and restitution in case of accidents causing injury or death. In this study, it is determined that from the road user perspective, the accident cost is equal to 40 percent of the accident cost of societal perspective. Hence, from the road user perspective, $k_1 = 0.4$ and $k_2, k_3 = 1$ and $k_4, C = 0$. The optimal speed from a societal perspective is 73 km/h and the optimal speed from a road user perspective is 82 km/h.

5. Comparison of results with other countries

In a multi-lane motorway divided by a median barrier in Sweden, the optimal speed is 110 km/h. The speed limit is 110 km/h and the current average speed is 109 km/h. In Norway, the optimal speed from a societal perspective is 100 km/h and the speed limit is 90 km/h. The current average speed is 95 km/h [2]. In Australia, the optimum speeds on rural freeways (dual carriageway roads with grade-separated intersections) would be 110 km/h [3]. Table 3 compares the results in Elvik [2] and Cameron [3] with those of the present study.

There is a significant difference between the results in Iran and those in Sweden, Norway, and Australia; this difference results from the

Table 2
Societal costs according to different speeds (km/h) in Iran's motorway (8740IRR = 1USD) in one year.

Societal cost	Equation of Societal cost (USD)	Optimum
Accident	$y = 0.04540927014\ V^{4.1} + 186.2741057\ V^2 + 219.8848497\ V^{1.5}$	The lowest available speed
Travel time	$y = 761613330.629499\ V^{-1.02047}$	In the highest available speed
Pollutants	$y = -3854902 - 0.0012451262262953\ V^4 + 0.000127\ V^5 + 85911424\ V^{-1} - 592612312.558\ V^{-2} + 23241333.782853\ V^{-0.5} + 243265.238\ V^{0.5} + 851160898361.978\ e^{-v} - 4.641\ E-47e^v$	Objective value: 2236340$ $V = 74$ km/h
Fuel	$y = -29254981.33 + 134692.3061\ V + 34.6429614\ V^2 + 0.000133724\ V^5 + 4807522.692\ V^{-1} - 3096112512\ V^{-2} + 222590275.6\ V^{-0.5} + 1.04068E + 13\ e^{-v}$	Objective value: 6573852 $ $V = 74$ km/h
Societal perspective	$y = -4.641\ E - 47e^v + 0.000260724\ V^5 + 0.04540927014\ V^{4.1} - 0.0012451262262953\ V^4 + 220.9170671\ V^2 + 219.8848497\ V^{1.5} + 134692.3061\ V + 243265.238\ V^{0.5} + 245831609.4\ V^{-0.5} + 90718946.69\ V^{-1} + 761613330.629499\ V^{-1.02047} - 3688724825\ V^{-2} + 1.1258E + 13\ e^{-v} - 33109883.33$	Objective value: 21428593.64 $ $V = 73$ km/h

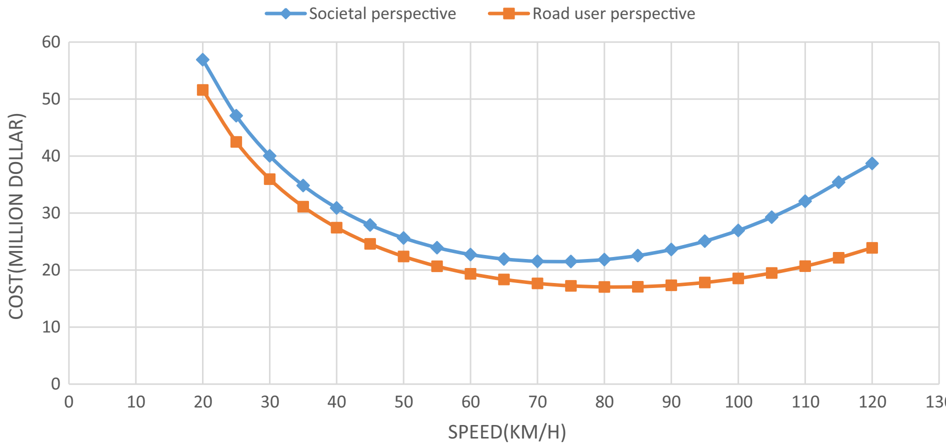

Fig. 2. Costs from societal and user perspectives in different speeds.

difference in the costs between Iran and these three countries. Also, the functions of fuel consumption and pollutant emission are different.

The optimal speed of roads with a specific geometric plan varies from society to society; it largely depends on the estimated cost of accidents, the value of time in the society, and technological factors such as safety, pollutant emission, and fuel consumption.

The results indicate that the optimal speed in Iran is lower than those in Sweden, Norway, and Australia. This is because of average family income in Iran. As this figure is used in calculating the value of a person's time, the most significant factor in increasing the optimal speed, the resulting optimal speed will be lower. Also, the fuel consumption of the vehicles currently used in the transportation fleet in Iran is relatively high and as a result, other factors in calculating societal cost become relatively less influential; this prevents the optimal speed from being higher.

6. Conclusion

Based on a deductive approach, a simple model for calculating the societal cost of travel was proposed in this paper. To test the validity of the proposed model, it was applied to the Shiraz-Marvdasht motorway, which is one of the most traversed routes in Iran. In the following, a summary of the obtained results is given:

First, it was illustrated that maximum speed limits are always set to be higher than the optimal speed and they are enforced in a way that the statistical mode of travel speed be as close to the optimal speed as possible in order to ensure maximum efficiency and reduce travel societal costs.

Second, the case study data was applied to the presented model and the following results were obtained: from a societal perspective, the optimal cost is incurred at a speed of 73 km/h and from a road user perspective the optimal speed is 82 km/h while the average speed of passing vehicles in 2011 was 82 km/h.

Finally, the case study results were compared with cases from Sweden, Norway, and Australia and the results showed that the optimal speed of roads with a specific geometric plan varies from society to society.

The optimal speed can be calculated in other urban ways and in suburbs. However, it should be noted that in urban ways, one can cover the demand if the optimal speed is used as the speed limit. This is seldom the issue in suburbs; the effect can be seen in the change of users' choice of transportation type.

Table 3
Optimal speed in Norway, Sweden, Australia, and Iran. Source for columns 2 and 3: Elvik [2]. Source for column 4: Cameron [3].

	Norway	Sweden	Australia	Iran
Optimal speed limits (km/h) according to societal perspective	100	110	110	**73**
Optimal speed limits (km/h) according to road user perspective	110	120	–	**82**
Current speed limits (km/h)	90	110	110	**110**
Current mean speed of travel (km/h)	95	109	–	**82**

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