Efficiency Analysis of Road Safety Pillars by Applying the Results of a Structural Equations Model in Data Envelopment Analysis

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Abstract

Assessment of road safety performance of countries and their comparison is essential in guiding future decisions. The objective of this study is to search for effective safety pillars in road safety capacity strengthening based on the experiences of the leading countries. In this study, we first try to use the results of a structural equations model with partial least squares approach to select the index as the representative index of each road safety pillar. Then, using the data envelopment analysis method, the ratio of the fatality rate to the sum of five calculated weights for a set of developing countries is calculated and the analysis of the efficiency and ranking of the countries takes place. Through the data envelopment analysis, the inefficiency of the 15 countries was calculated and ranked accordingly. The results of structural equation model showed that Iran has had a fair amount of activity in the field of road infrastructure safety. According to the results of this analysis, Iran is in the 15th position after South Africa, which indicates the poor road safety status and the quantitative and qualitative inadequacy of activities undertaken in some of the country's road safety pillars. In this analysis, the three countries of Romania, Poland and Turkey had the lowest inefficiency, each of which could be a benchmark for the activities of other countries. The results showed that only the country of Poland was identified as a pattern of activities in Iran.

Keywords: Road safety pillars, road safety performance analysis, data envelopment analysis, structural equations model.

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1. Introduction

To reach a high level of road safety in countries, policy makers need to take advantage of safety interventions and to monitor performances so that they can take the outcomes by road crashes under control. This monitoring can be addressed by road safety performance indicators (RSPIs). The RSPIs are considered as tools for policy makers by means of which they make sure how effective their interventions were. Moreover, assessing the countries' road safety performances has a great role in orienting the decisions for future works. For doing so, the efficiency of the countries' activities must be calculated in order to deliberate an appropriate process for prospective decisions. Assessing the performance of countries who have well-bred in road safety in recent decades suggest that they have earned this growth by enhancing the efficiency of their activities.

Using the successful experiences of the leading countries, planning the action outlines, and developing the road safety services all need nationwide strategies and a high volition to implement them. For this reason, in 2010 a United Nations' General Assembly resolution proclaimed 2011–2020 the Decade of Action for road safety, with a global goal of stabilizing and then reducing the forecasted level of global road fatalities by increasing activities conducted at national, regional and global levels [United Nations, n.d.]. The global plan comprises five pillars including road safety management, safer roads and mobility, safer vehicles, safer road users, and post-crash response. Each pillar encompasses a set of activities which require mathematical analyses to apply all RSPIs in comparing the countries' performances. The objective of this study is to search for effective safety pillars in road safety capacity strengthening based on the experiences of the leading countries. Identifying the leading country was carried out by an efficiency analysis process. Initially, the assessment result is explained by ranking the countries. Using the ranking grades, the road safety weaknesses were recognised in each country who need to follow actions in benchmark countries in order to raise its efficiency score.

Using the results of a structural equation model with the partial least squares approach, enfolding RSPIs for each road safety pillar, this study assigns an indicator to each pillar which would represent its magnitude. Afterwards, the proportion of road fatality rate to the weighted sum of all pillar-related indicators are calculated for each country using the data envelopment analysis through which the efficiency analysis and country ranking is fulfilled. This ranking process is projected to find Iran's position among the leading developing countries after which advices are offered to enhance road safety and its efficiency in this country. Meanwhile, using the ideal values earned for each pillar, one could clarify which pillar would meet more weakness levels.

2. Literature Review

Best practice analysis has been a major concern of road safety practitioners so as to find benchmarks which could actually lead actions to gain the highest efficiency achievements. Data Envelopment Analysis with thirty years of scholarly literature [Emrouznejad et al. 2008; and Cook and Seiford, 2009] is the main method which could have best played the major role in such analyses. As a means to identify traffic safety best practice, Odeck [2006] used DEA to investigate target achievements of the operational units of the Norwegian Public Roads Administration (NPRA) charged with traffic safety services. Using accident rates as surrogates of safety performance measures, the DEA can be deployed to endogenously construct non-linearly arranged set of best practice countries when the weight of each safety performance measure is endogenously determined based on optimization techniques [Vaziri, 2010]. Accordingly, The DEA delineates the best practice frontiers and realistic target values. In 2011, Shen et al. enhanced the DEA model into a generalized multiple layer analysis to further embody multilayer hierarchical structures of inputs and outputs defined in the road safety management system. A master study in European Union called road safety data collection, transfer, and analysis (DaCoTA) aimed at building a composed Road Safety Index (RSI) in which indicators describing the road safety outcome or output of a country are combined into one figure [Bax et al. 2012]. In the context of best practice analysis, the index facilitates easy comparisons between countries to inspire them to increase their efforts and improve road safety in their country. Concurrently, Shen et al [2012] adopted the categorical DEA road safety model after clustering the countries with inherent similarity in their practices so as to identify best-performing and underperforming countries in each cluster as well as practical yet challenging target for each underperforming country.

The approach was developed in United States by Egilmez and McAvoy [2013] who used Malmquist index model to assess the relative efficiency and productivity of US states in decreasing the number of road fatalities. Behnood et al. [2014] presented a model to evaluate the efficiency related to the measures annually implemented throughout 30 provinces of Iran by introducing an inefficiency index defined as the proportion of weighted sum of road fatality risk indices to the weighted sum of road intervention indicators. Alper et al [2015] estimated the relative efficiency of 197 local municipalities in traffic safety during 2004–2009, using DEA. They used inputs reflecting the resources allocated to the local municipalities (such as funding), outputs include measures that reflect reductions in accidents (such as accidents per population), and intermediate variables known as safety performance indicators (SPI): measures that are theoretically linked to crash and injury reductions (such as use of safety belts).

3. Methodology

Data in this study are adopted from the Global Status Report on Road Safety 2015 (WHO, 2015). The fatality rate introduced by the Legal Medicine Organization of Iran has been different with the values declared by World Health Organization (WHO) which is due to the under-reporting reasons.

The data used in this study include road safety performance indicators related to five road safety pillars consisting of road safety management, safer roads and mobility, safer vehicles, safer road users, and post-crash response which are shown in Table 1. The data existing in the database were directly used to create the structural equations model (SEM). The database includes the road safety data related to 102 countries.

Efficiency analysis using the Data Envelopment Analysis (DEA) was carried out with the purpose of identifying the Iran's position and weaknesses in road safety development amongst leading developing countries. At the first step, the database was established to assess the weight of each performance indicator in each group of the road safety pillar by entering them in a structural equations model. Once the model was created, assessed and confirmed, the magnitude of each pillar was calculated for each country using the earned factor load and it was considered as the input data in the data envelopment analysis. The framework diagram to show the study design and the process to achieve results is shown in Figure 1.
The purpose by modelling in this study was to attain the weights attributed to 22 indicators applied to be merged in five road safety pillars.

The structural equations model was established using the SmartPLS software. The SEM is a principal method in analysing the multivariate structures [Kirschkamp, 2007]. This method comprises a set of statistical models for modelling the relation between independent and dependent variables (structural model) or latent and observable variables (measurement model) which consists of factor analysis, regression models or the path analysis [Ulman, 2006; Hoyle, 2012; Mueller, 2013]. In modelling the structural equations, the confirmatory factor analysis is a main application in the measurement model. The main purpose of the confirmatory factor analysis is to determine the power of a predefined factor model using a set of observed data [Mohsenin and Esfidani, 2014].

As mentioned before, the road safety measures are encompassed in five road safety pillars. Therefore, the road safety is considered as latent variable attributable to the five pillars. The observed variables in the model consist of the 22 performance indicators (see Figure 2). In this study, road safety has been considered as a second order latent variables in relation to the five road safety pillars considered as the first order latent variables. The 22 indicators within the five pillars were the observed variables in the model. In developing the model with the second order latent variable in the partial least square approach, all indicators must somehow be connected to the second order latent variable, since the relations between observed indicators and the second order latent variables are not analyzed in the PLS approach. Therefore, to clarify the model, the indicators connected to the second order latent variables are converted to the latent variables themselves [Davari and Rezazadeh, 2013].

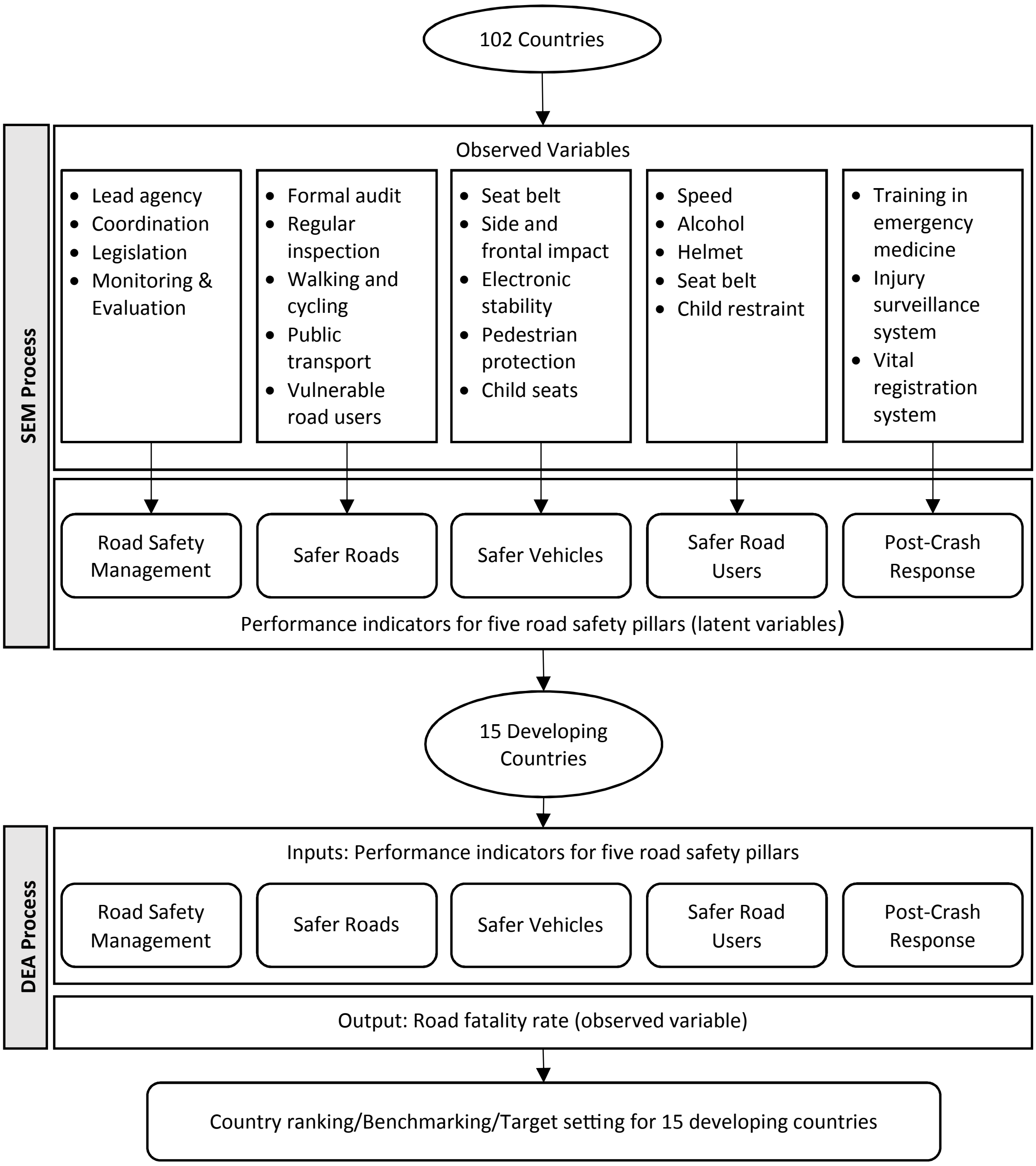

Figure 1. Study design

Table 1. Road safety performance indicators in five road safety pillars

Road Safety Pillar		Intervention		Value	Symbol
Road Safety Management	RSM	Lead agency	Lead agency Funded Lead agency	1: both case exist 0.5: one case exists 0: no case exists	Q_{11}
		Coordination		1: Exists 0: Not exists	Q_{12}
		Legislation			Q_{13}
		Monitoring and Evaluation			Q_{14}
Safer Roads and Mobility	SRM	Formal audit		1: Exists 0.5: Subnationally exists 0: Not exists	Q_{21}
		Regular inspection			Q_{22}
		Walking and cycling			Q_{23}
		Public transport			Q_{24}
		Vulnerable road users			Q_{25}
Safer Vehicles	SV	Seat belt	Seat belt Seat-belt anchorages	1: both case exist 0.5: one case exists 0: no case exists	Q_{31}
		Side and frontal impact	Frontal impact Side impact		Q_{32}
		Electronic stability		1: Exists 0: Not exists	Q_{33}
		Pedestrian protection			Q_{34}
		Child seats			Q_{35}
Safer Road Users	SRU	Speed		Efficiency score assigned by World Health Organization	Q_{41}
		Alcohol			Q_{42}
		Helmet			Q_{43}
		Seat belt			Q_{44}
		Child restraint			Q_{45}
Post-Crash Response	PCR	Training in emergency medicine	For doctors For nurses	1: both case exist 0.5: one case exists 0: no case exists	Q_{51}
		Injury surveillance system		1: Exists 0: Not exists	Q_{52}
		Vital registration system			Q_{53}

Since the partial least square is a variance-based approach, the average extracted variance for each latent variable must be more than 0.5. To explain the average extracted variance for each latent variable, the observed variables with the least factor loads must be removed. The least factor load for each observed variable in the measurement model is 0.4 for which the lower values are removed in the model. In this study, 14 developing countries were considered as following to compare Iran with the other similar countries and identifying the target indicators for Iran:

- Emerging economies known as BRICS member states including Brazil, Russian Federation, India, China, and South Africa;
- Developing countries whose road safety management system has already been structured on the basis of the Global Road Safety Facility guidelines [BlissandBreen, 2013; and BlissandRaffo, 2013] including Argentina, Malaysia, and Poland; and
- Six countries which are immediately located above Iran in term of Human Development Index [World Bank Group, 2015] including Mexico, Kazakhstan, Turkey, Lebanon, Oman, and Romania.

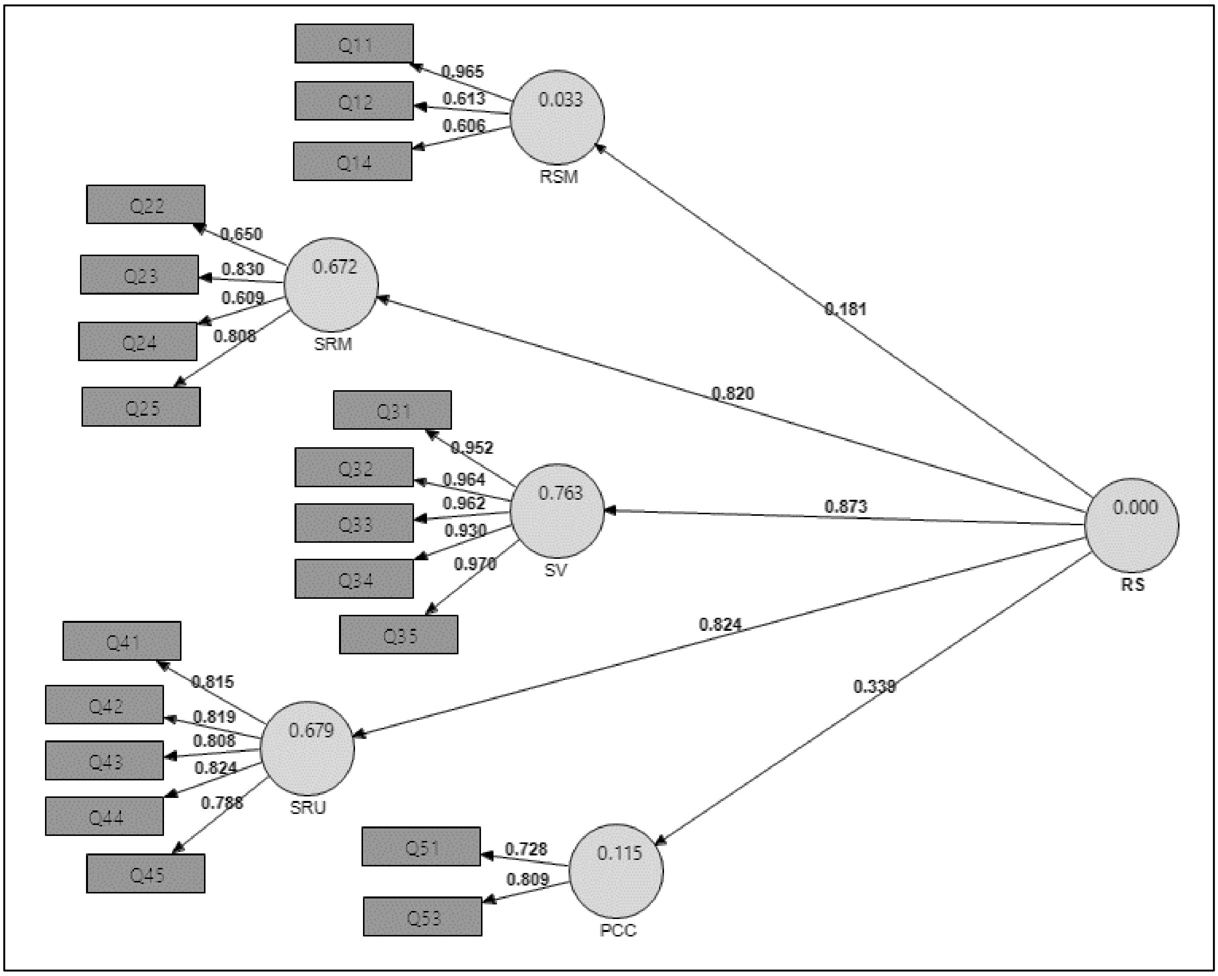

Figure 2. Relations between variables in the SEM

In a previous study [Behnood, 2018], using the same 15 countries, a virtual performance indicator was defined as the success score of each pillar in the decade of action for each country to achieve the targets of decreasing road fatalities. The virtual indicator as well as two other indicator classes (intervention outputs and final outcomes) went simultaneously into an optimization problem using a nonlinear multiobjective DEA approach. So, the analysis relied on the 15 countries characteristics to define the five pillars' weights. In the current study, the weights were extracted by SEM for 102 countries.

All input data to use in the analysis based on the classification in Table 1 are shown in Table 2 for Iran and the other 14 countries. Having created the SEM using the calculated factor loads in the measurement model, the indicators in each group were multiplied with the attributed factor load to form a single indictor for each road safety pillar:

$$X_i = \sum_j Q_{ij} \times f_{ij} \qquad (1)$$

Table 2. Road safety performance indicators classified by results in road safety management system

			Road Safety Management		Safer roads and mobility					Safer vehicles					Safer road users					Post-crash care	
Country	Income*	Fatality/100,000 inhabitants	lead agency	management functions	formal audit	regular inspection	walkingand cycling	public transport	vulnerable road users	seat-belt	frontal and side impact	electronic stability	pedestrian protection	Child seats	speed	drink driving	helmet	seat belt	child restraint	Training in emergency medicine	injury surveillance system
Iran	M	32.1	0.5	1.0	0.0	1.0	0.5	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.7	0.8	0.5	0.7	0.0	1.0	1.0
Brazil	M	23.6	1.0	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.0	0.0	1.0	0.7	0.8	0.6	0.7	0.6	1.0	1.0
Russian Federation	H	18.9	1.0	1.0	1.0	1.0	0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0	0.8	0.6	0.6	0.7	0.6	1.0	1.0
India	M	16.6	1.0	1.0	1.0	0.0	1.0	1.0	0.5	1.0	0.0	0.0	0.0	0.0	0.3	0.4	0.4	0.4	0.0	1.0	0.0
China	M	18.8	1.0	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.8	0.9	0.6	0.8	0.0	0.5	1.0
South Africa	M	25.4	1.0	1.0	1.0	1.0	0.0	1.0	1.0	0.5	0.0	1.0	1.0	1.0	0.3	0.4	0.5	0.2	0.0	1.0	0.0
Argentina	M	13.6	0.5	1.0	1.0	1.0	0.5	1.0	0.5	1.0	1.0	0.0	0.0	0.0	0.7	0.6	0.6	0.6	0.0	1.0	1.0
Malaysia	M	24.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	0.0	1.0	0.6	0.5	0.5	0.4	0.0	1.0	0.0
Poland	H	10.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.8	0.9	0.7	0.8	1.0	0.0
Mexico	M	12.3	0.0	0.0	0.0	1.0	0.5	0.5	0.0	0.5	0.0	0.0	0.0	0.0	0.5	0.5	0.6	0.7	0.4	1.0	0.0
Kazakhstan	M	24.2	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.0	1.0	1.0	0.7	1.0	1.0
Turkey	M	8.9	1.0	1.0	1.0	1.0	0.5	1.0	0.0	1.0	1.0	1.0	1.0	1.0	0.4	0.3	0.3	0.2	0.3	0.5	1.0
Lebanon	M	22.6	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.2	0.3	0.0	1.0	0.0
Oman	H	25.4	1.0	1.0	1.0	1.0	0.5	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.9	0.8	1.0	0.9	0.5	1.0	1.0
Romania	M	8.7	0.5	0.7	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	0.5	0.8	0.9	0.7	0.7	1.0	0.0

* H= High income, M= Middle income

In this equation, f_{ij} is the factor load earned by the SEM for the j[th] variable (Q_{ij}) in the set of performance indicators related to i[th] road safety pillar. Thereby, the magnitude value of each pillar was calculated for each of the 15 developing countries that was used as the input value in the DEA model. The indicator of road fatality rate per 100,000 population was also considered as the output value in the analysis.

Data envelopment analysis is a nonparametric method which is used to calculate the efficiency of decision making units (DMUs). The first DEA model was created by Charnes, Cooper and Rhodes in 1978 by whose names were named as the CCR model. Supposing m inputs and s outputs for each DMU and purposing to maximize the efficiency, the model is as following [Mehregan, 1391]:

$$\text{Max } \theta_0 = \frac{\sum_{r=1}^{s} u_r y_{r_0}}{\sum_{i=1}^{m} v_i x_{i_0}} \qquad (2)$$

S.t.

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1$$

$$u_r \text{ و } v_i \geq 0$$

In this equation, u_r and v_i are the weights assigned to outputs and inputs respectively and θ_0 is the relative efficiency of the considered unit. The decision variables in the problem above are the weights of the model. In this model, if the variables u_r being much high or the variables v_i being much low, the value of the proportions can be unlimited or extreme. To avoid this, a constraint enters the model which keeps the proportions lower or equal to one.

The above CCR model is a fractional programming which maximizes the desired outputs. Nonetheless, since the output considered in this study implies the road fatality rate as an undesirable output, and besides that we need to convert the model to a linear model, the objective function and the constraints are written as below:

$$\text{Min } \theta_0 = u_r y_r \qquad (3)$$

S.t.

$$\sum_{i=1}^{m} v_i x_i = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \geq 0$$

$$u_r \text{ و } v_i \geq 0$$

In this model, y_r is the road fatality rate and x_i is the magnitude value of each road safety pillar which was calculated in advance using the SEM process and the equation 1. According to the model, the units earning the efficiency value of 1.0 are known as efficient units (best-performing countries) whereas the countries which earned efficiency values greater than one are known as inefficient units (under-performing countries). The inefficient units need to benchmark efficient units to enhance their efficiency value. To do so, the shadow prices in the DEA model are applied. The benchmark units for each inefficient unit are identified by nonzero shadow prices earned through solving the DEA problem. That way, using the shadow price belonged to the considered unit and the attributed benchmark, one can calculate target values for each road safety pillar. By assessing the difference between the existing value of each pillar and its target value, the highest weaknesses in each unit can be identified. The equation to calculate target values in each DMU is:

$$Target_{i.A} = \sum_{b=1}^{B} \left(\frac{\lambda_b}{\boldsymbol{\theta}_A} \times x_{i.B} \right) \qquad (4)$$

Where B is the number of benchmark units for the underperforming unit A, λ_b is the shadow price for the benchmark unit b, and θ_A is the inefficiency rate calculated for the unit A.

4. Results

The magnitude value for the 15 developing countries are calculated in Table 3 which would be used as the inputs of the DEA. The fatality rate per 100,000 population is also used as the DEA output value. The results in this table conclude that:

- In the field of road safety management, Iran has worked actively to some extent. Two countries Lebanon and Mexico had no activity and China has had a little activity.
- In the field of road infrastructure safety, Iran has been somewhat active, but the most activities were in the countries of China and Poland.
- In the field of safer vehicles, in relation to the indicators set by the World Health Organization in 2015, Iran did not have any activity. In this context, the four countries of Poland, Romania, Russia and Turkey were the most active ones.
- In the field of safer road users and enforcement activities, Iran's actions are ranked among the middle classes, and Kazakhstan has been the most active country. South Africa also had the least activity in this area.
- In the field of post-crash response and emergency management and rescue, most countries, including Iran, were on the same level, with Romania and Turkey having the lowest levels of activity.

It should be noted that these levels of activity are only quantitatively expressed and do not indicate the quality and effectiveness of them in reducing the fatality rate, as it is considered that Iran has the highest rate of traffic fatalities in 15 countries. Hence, the efficiency of activities to reduce this final index is calculated by computing the composite indicator based on the data envelopment analysis. During the data envelopment analysis, the inefficiency of the 15 countries was calculated and based on that, the ranking was made in Table 4. According to this table, Iran is in the fifteenth place after South Africa, indicating the poor road safety status and the quantitative and qualitative inadequacy of activities undertaken in some of the country's road safety pillars. In this analysis, the three countries of Romania, Poland and Turkey have the lowest inefficiency, each one of which can be as a benchmark for the activities of other countries. By examining the shadow prices, it is noted that Poland alone has been identified with a value of 3.116 shadow price as a benchmark for Iranian activities. Thus, the target values for each pillar are calculated using equation 4 and the difference with the current situation as described in Table 5. The table shows that the most evolution required in road safety measures is the pillar of safer vehicles. For this purpose, the indicators related to vehicle safety and other components in Poland can be a good benchmark for the development of road safety in Iran. In this country, in the area of vehicle safety, the full capacity of road safety standards has been used, such as electronic sustainability and pedestrian protection. Two other pillars, including road safety management and safer roads and mobility, have been fully developed.

Table 3. Calculated magnitudes of the five road safety pillars

Country	DMU	Magnitude of the road safety pillar (DEA input)					Fatality rate
		P_1 (RSM)	P_2 (SRM)	P_3 (SV)	P_4 (SRU)	P_5 (PCR)	(DEA output)
Iran	1	1.27	1.10	0	0.66	1.30	32.1
Brazil	2	1.44	1.25	0.62	0.84	1.30	23.4
Russian Federation	3	1.44	0.90	1.05	0.81	1.30	18.9
India	4	1.44	0.87	0.21	0.37	1.30	16.6
China	5	0.89	1.41	0.42	0.76	1.30	18.8
South Africa	6	1.44	1.10	0.73	0.34	1.30	25.1
Argentina	7	1.27	1.10	031	0.61	1.30	13.6
Malaysia	8	1.44	1.26	0.84	0.49	1.30	24.0
Poland	9	1.44	1.41	1.05	0.91	1.30	10.3
Mexico	10	0	0.74	0.10	0.66	1.30	12.3
Kazakhstan	11	1.44	1.10	0	1.11	1.30	24.2
Turkey	12	1.44	0.95	1.05	0.37	0.96	8.9
Lebanon	13	0	0.38	0	0.37	1.30	22.6
Oman	14	1.44	1.10	0	1.01	1.30	25.4
Romania	15	0.72	1.25	1.05	0.89	0.69	8.7

Table 4. Calculated road safety inefficiency score

Country	Rank	Inefficiency (θ)	Country	Rank	Inefficiency (θ)
Romania	1	1	Kazakhstan	9	2.03
Poland	2	1	Lebanon	10	2.19
Turkey	3	1	Brazil	11	2.27
Mexico	4	1.19	Oman	12	2.29
Argentina	5	1.32	Malaysia	13	2.33
India	6	1.61	South Africa	14	2.44
China	7	1.83	Iran	15	3.12
Russian Federation	8	1.83	---	---	---

Table 5. Calculated target values for road safety pillars in Iran

Road safety pillar	Magnitude of the road safety pillar		
	Existing status	Target value	Needed increase
Road safety management	1.27	1.44	0.17
Safer roads and mobility	1.10	1.40	0.30
Safer vehicles	0	1.05	1.05
Safer road users	0.66	0.91	0.25
Post-crash response	1.30	1.30	0
Fatality Rate	32.1	10.3	-21.8

5. Discussion

Target setting for road safety performance indicators has always been a critical issue of concern for road safety policy makers. This study tries to find an optimum way to find benchmarks for road safety development in Iran in accordance to the countries slightly yet more developed in some national indices. The results show Poland as a rational benchmark, which could best align the road safety pillars in term of its road safety performance indicators as well as the interventions within each pillar. The results imply that the highest revolution is needed in providing safer vehicles, the capacity for which has thoroughly been unused in all components including new technologies for seat-belt, frontal and side impact, electronic stability, pedestrian protection, and child seats. The target values for the post-crash response, designates it as a well-defined practice which would not need any change at the current level. The results in this study are much close to the results earned in the previous study which used a success indicator as a virtual intermediate outcome for each road safety pillar in the same 15 countries [Behnood, 2018].

6. Conclusion and Suggestions

By analyzing the data of five road safety pillars in 102 countries, a structural equation model has been used to search for the relationship between the components of these five pillars. Thus, the magnitude of each pillar can be calculated according to the importance of each component involved in it, which indicates the quantity and performance of each pillar in each country. The results of the structural equation model show that Iran has had a fair amount of activity in the field of road infrastructure safety. Among these countries, 15 developing countries including Iran were selected to compare and determine the patterns of activity and were included as decision-making units in data envelopment analysis. The magnitude of each pillar has been calculated for fifteen developing countries and has been used as input for data envelopment analysis. The fatality rate index for 100,000 population was also used in the analysis as the output value for each country. Through the data envelopment analysis, the inefficiency of the 15 countries was calculated and ranked accordingly. According to the results of this analysis, Iran is in the 15th position after South Africa, which indicates the poor road safety status and the quantitative and qualitative inadequacy of activities undertaken in some of the country's road safety pillars. In this analysis, the three countries of Romania, Poland and Turkey had the lowest inefficiency, each of which can be a benchmark for the activities of other countries. The results showed that the only country of Poland was identified as a benchmark of Iran's activities. The results also showed that the most evolution required in road safety measures in Iran was related to the safety of vehicles. Accordingly, indicators related to vehicle safety and other components in Poland could be a good benchmark for the development of road safety in Iran.

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