ROAD SAFETY EVALUATION AND TARGET SETTING USING DATA ENVELOPMENT ANALYSIS

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ABSTRACT

At present, comparisons between countries in terms of their road safety performance are widely conducted in order to better understand one's own safety situation and to learn from other countries. In this respect, crash data such as the number of road fatalities and casualties are mostly investigated. However, the absolute numbers are not directly comparable between countries. Therefore, the concept of risk, which is defined as the ratio of road safety outcomes and some measure of exposure (e.g., the population size, the number of vehicles, or kilometres travelled), is often used in the context of benchmarking. Nevertheless, these risk indicators are not consistent in most cases. In other words, countries may have different evaluation results or ranking positions using different exposure information. In this study, data envelopment analysis (DEA) as a performance measurement technique is adopted to provide an overall perspective on a country's road safety situation, and further assess whether the road safety outcomes registered in a country correspond to the numbers that can be expected based on the level of exposure. More specifically, 2007 data for 26 European Union (EU) countries (except Malta) in terms of the number of inhabitants, passenger cars and passenger-kilometres travelled are used as the model's inputs and the number of road fatalities as the output. As a result, an overall road safety efficiency score is computed for each country and the ranking of countries in accordance with their efficiency scores is evaluated. Furthermore, based on the model results, best-performing and underperforming countries are identified, and specific benchmarks are indicated for each underperforming country. Moreover, challenging targets are given for each underperforming country by learning from its benchmarks, enabling policymakers to recognize the gap with other countries and further develop its own road safety policy.

1 INTRODUCTION

Road safety is an important issue not only because of the lost travel time or cost of property damage, but mainly because of the loss of human life and serious injuries sustained. Since more and more countries are taking steps to improve their road safety situation, there is a growing need for a country to compare its own road safety performance with that of other countries for the purpose of better understanding its relative safety situation, and moreover, trying to learn from those better-performing countries in terms of road safety policy making and target setting [OECD, 1994].

Currently, the road safety situation of a country is mostly evaluated by means of crash data such as the number of road fatalities and casualties. However, the absolute numbers are not directly comparable between countries. Therefore, the concept of risk [ETSC, 2003], which is defined as the ratio of road safety outcomes and some measure of exposure, is often used in the context of benchmarking. The number of fatalities per million inhabitants, the number of fatalities per million passenger cars, and the number of fatalities per 10 billion passenger-kilometres travelled (pkm) are three widely used risk indicators [EC, 2009]. However, they are not consistent in most cases. In other words, countries may have different evaluation results or ranking positions using different exposure information, which baffles the decision makers in distinguishing best-performing countries from underperforming countries. Moreover, from the target setting point of view, numbers rather than rates are much more preferred since a declining rate such as the fatalities per numbers of passenger-kilometres travelled may conceal an increase in the raw number of fatalities [ERSO, 2006]. Consequently, an analytical research tool that can represent an overall perspective on a country's road safety situation (in ratio, which makes countries comparable), but is also able to provide improvement potential for those underperforming countries (by numbers), is valuable.

In this study, data envelopment analysis (DEA) as a performance measurement technique is adopted to show an overall road safety picture by taking all three aspects of exposure into account. It further assesses whether the road safety outcomes registered in a country correspond to the numbers that can be expected based on the level of exposure. More specifically, by means of this multi-input multi-output methodology the most optimal performance of a particular country is determined in terms of efficiency (i.e., an efficient transformation of input or exposure into output or road safety outcomes) thereby using the information on all other countries in the data set, i.e., it is based on relative self appraisal. Moreover, based on the efficiency score, best-performing and underperforming countries can be identified and challenging targets can be set for each underperforming country.

In this paper, the data for 26 European Union (EU) countries (the EU27 except Malta) in terms of the number of inhabitants, passenger cars and passenger-kilometres travelled are used as the model's inputs and the number of road fatalities as the output (the number of serious casualties is also a possible output. However, a larger amount of uncertainty is linked to this variable as its definition often differs across countries, which makes the data less reliable and comparable). As a result, an overall road safety efficiency score is computed for each country and the ranking of countries in accordance with their efficiency score is evaluated. Furthermore, based on the model results challenging targets can be given for those underperforming countries by learning from their benchmarks enabling policymakers to recognize the gap with those best-performing countries and further develop their own road safety policy.

The remaining of the paper is structured as follows. In Section 2, three main risk indicators, i.e., the mortality rate, the fatality risk and the fatality rate, are introduced. The idea of setting quantitative road safety targets is presented in Section 3. Section 4 illuminates the advantages of using the DEA approach and specifies its different mathematical forms. The applications of DEA to the road safety context and the results from the model are provided and discussed in Section 5. The conclusions are summarized in Section 6 along with guidelines for future research.

2 RISK INDICATORS

Reduction of risk and consequent death, injury and damage is the key objective of policy concerning road safety. In order to obtain numerically reliable estimates of risk to road users, recorded numbers of fatalities or casualties are usually related to measures of exposure to risk, which is the main form of risk assessment in road transport between countries [ETSC, 2003].

Concerning exposure to risk, population data are most commonly used since nearly all countries have accurate data. The corresponding risk indicator, i.e., the number of fatalities per million inhabitants, is known as *the mortality rate* and regarded as an important criterion for road safety. However, for the comparison of traffic risks this indicator has the disadvantage of leaving the level of motorization out of account. Accordingly, estimation of exposure to risk in terms of traffic volume is introduced representing *the fatality risk*, which is defined as the number of fatalities per vehicle or passenger kilometres travelled. However, the definition of this exposure measure differs widely across countries. Furthermore, not all countries collect data on motor vehicle use. As a result, a third risk indicator---defined as the number of fatalities per million passenger cars, which is also called *the fatality rate*---are substituted.

In the latest EU energy and transport in figures report [EC, 2009], 2007 data related to the above three risk indicators were collected for the 27 EU countries, which are Austria (AT), Belgium (BE), Bulgaria (BG), Cyprus (CY), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (EL), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), Malta (MT), the Netherlands (NL), Romania (RO), Poland (PL), Portugal (PT), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), and United Kingdom (UK). Country rankings in decreasing order of safety are shown in Table 1.

Table 1: Rankings of the 27 EU countries based on the three road safety risk indicators in 2007 [EC, 2009]

Fatalities per million inhabitants		Fatalities per 10 billion pkm		Fatalities per million passenger cars	
MT	29	UK	44	MT	54
NL	43	SE	46	NL	97
UK	50	NL	47	UK	106
SE	51	MT	56	SE	111
DE	60	DE	56	DE	120
FI	72	FI	59	LU	135
DK	74	FR	62	IT	145
FR	75	LU	64	FR	148
IE	78	IT	64	FI	150
AT	83	DK	72	AT	164
ES	85	IE	80	ES	179
EU27	86	EU27	88	IE	182
IT	86	BE	94	EU27	187
LU	90	AT	94	DK	199
PT	92	ES	108	BE	213
BE	100	SI	125	PT	225
CY	114	PT	128	CY	227
SK	116	EL	158	CZ	291
CZ	118	CY	158	SI	293
HU	123	CZ	163	EL	338
RO	130	LT	187	EE	364
BG	131	EE	193	PL	399

EL	141	PL	229	HU	413
SI	145	LV	234	SK	453
EE	146	SK	235	LT	465
PL	146	HU	289	LV	485
LV	184	BG	289	BG	523
LT	219	RO	448	RO	782

Notes:
Fatalities: all fatalities on the road for 2007
Inhabitants: sum of the population at 1 January 2007 and 1 January 2008 divided by two
pkm: passenger-kilometres of cars plus passenger-kilometres of motorised two-wheelers
Passenger cars: sum of the stock of vehicles for 2006 and 2007 divided by two

It can be seen that the ranking positions of these 27 EU countries based on the three risk indicators are different to a great extent. For example, UK ranks first with respect to the fatalities per 10 billion pkm, however, it is not the case when considering the other two exposure information. In fact, it happens to almost all of the countries. Such kind of inconsistencies baffles the decision makers in identifying best-performing countries and deciding the extent to which these countries can be learned from. Consequently, an analytical research tool that can provide an overall perspective on a country's road safety situation is valuable. In this study, data envelopment analysis will be adopted to show an overall road safety picture by taking all three aspects of the exposure into account[1]. Using the model linking inputs with outputs, the most optimal performance of each country will be determined in terms of efficiency, and the ranking of countries in accordance with their efficiency score will be evaluated (see Sections 4 and 5).

3 TARGET SETTING

If we argue that risk analysis makes a powerful contribution to the development of effective strategies and programmes for casualty reduction and crash prevention, then the setting of challenging yet achievable quantitative road safety targets (usually expressed in terms of final outcomes, e.g., reduction in the number of fatalities and serious injuries) serves as a significant catalyst that motivates the whole range of stakeholders (from individuals who use the roads in different ways to government agencies at all levels) to support such strategies and programmes to achieve the safer use of roads. The value of setting targets to reduce road fatalities and casualties and thereby improve road safety performance has been widely recognized [e.g., Elvik, 2001; Wong, 2006]. An increasing number of countries are implementing long term road safety strategies towards their reduction or eventual elimination (e.g., the Swedish Vision Zero [OECD/ITF, 2008]) within a framework of quantitative road safety targets.

In practice, setting a challenging yet achievable quantitative target, however, is by no means easy. Firstly, road safety targets represent the desired road safety results which a country wishes to achieve over a given timeframe. In other words, it requires a reasonable assumption about the future. However, estimates of what is likely to be achievable should not only be based upon information about the current road safety situation of a country itself (which is mostly concentrated on in the current research, such as [OECD, 2002]), but also try to incorporate other homogeneous countries' best practices.

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[1] Even though these three aspects are highly correlated, omitting anyone can have a major influence on the computed efficiency measures [Jenkins, 2003].

In this study, a new methodology is proposed to help setting valuable numerical road safety targets for underperforming countries. More specifically, by means of data envelopment analysis, the road safety outcomes registered in a country will be assessed based on its level of exposure, and a challenging target or improvement potential will be proposed using the information on all other countries in the data set. In other words, it will base the target of a particular country on the achievements that have already been realized by so-called best-performing countries.

4 DATA ENVELOPMENT ANALYSIS

Data envelopment analysis developed by Charnes, Cooper and Rhodes [Charnes et al., 1978] is a mathematical programming methodology to measure the relative efficiency of a homogeneous set of decision making units (DMUs), or countries in this case. Since its first introduction in 1978, DEA has been quickly recognized as a powerful analytical research tool for modeling operational processes in terms of performance evaluations, e.g., [Cherchye et al., 2006], benchmarking, e.g., [Hermans et al., 2009], and decision making, e.g., [Ertay et al., 2005], and it has been successfully applied to a host of different types of entities engaged in a wide variety of activities in many contexts [Emrouznejad et al., 2008]. In the following sections, advantages of using DEA and its different mathematical forms are presented.

4.1 Advantages of DEA

DEA as a powerful performance measurement technique has received significant attention in recent years due to its prominent advantages over other traditional methods. First of all, it provides a new way of obtaining empirical estimates of relations between multiple inputs and multiple outputs without resorting to a priori knowledge concerning their weights, and the inputs and outputs used in the model can be expressed in different units of measurement. In other words, the preliminary normalization (e.g., standardization) of raw data is not required, which is particularly convenient from a practical point of view and reduces the sensitivity of the results with respect to the specific normalization scheme that is used [Nardo et al, 2005]. Moreover, DEA assesses the relative efficiency of a particular unit (or country) by comparing it against all other ones, i.e., it is based on self appraisal, and the final efficiency score will be measured with respect to the best observed performance, which is different from other techniques that are based on the average observed or some predetermined performance [El-Mahgary et al, 1995]. Last but not least, by distinguishing between efficient units and inefficient units, DEA possesses the ability to determine the potential improvement for those inefficient units by indicating practical targets for them, which mostly attracts analysts and policy makers, and results in the widespread application of this technique [Amirteimoori et al, 2005, Hermans et al, 2009, Yang et al, 2009].

4.2 The primal DEA model

Mathematically, consider a set of n countries, each consuming m different inputs to produce s different outputs. The relative efficiency of a country is defined as the ratio of its total weighted output to its total weighted input, and the efficiency score of a particular country c, i.e., h_c, can be obtained by solving the following constrained optimization problem:

$$\begin{aligned} \max h_c &= \frac{\sum_{r=1}^{s} u_r y_{rc}}{\sum_{i=1}^{m} v_i x_{ic}} \\ s.t. \quad & \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \quad j = 1, \cdots, n \\ & u_r, v_i \ge \varepsilon, \quad r = 1, \cdots, s, \quad i = 1, \cdots, m \end{aligned} \tag{1}$$

where y_{rj} and x_{ij} are the rth output and ith input respectively of the jth country, u_r is the weight given to output r, v_i is the weight given to input i, and ε is a small non-Archimedean number [Charnes et al., 1984] for restricting the model to assign a weight of 0 to unfavorable factors. This fractional program is computed separately for each country to determine its optimal weights. In other words, the weights in the objective function are chosen to maximize the value of country c's efficiency ratio and meanwhile respect the less than unity constraint for all the countries including c itself. This effectively eliminates the difficult task of assigning suitable weights to each input and output factor.

Moreover, to simplify the calculation and avoid an infinite number of solutions[2], the above fractional program can be converted into a linear program which is known as *the multiplier form* of this problem:

$$\begin{aligned} \max h_c &= \sum_{r=1}^{s} u_r y_{rc} \\ s.t. \quad & \sum_{i=1}^{m} v_i x_{ic} = 1, \\ & \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0, \quad j = 1, \cdots, n \\ & u_r, v_i \ge \varepsilon, \quad r = 1, \cdots, s, \quad i = 1, \cdots, m \end{aligned} \tag{2}$$

The transformation is completed by constraining the efficiency ratio denominator in model (1) to a value of one. This model is run n times to identify the relative efficiency score of all countries by selecting optimal output and input weights. In general, a country is considered to be best-performing or efficient if it obtains an efficiency score of one whereas a score less than one implies that it is an underperforming country.

4.3 The dual DEA model

Using the duality in linear programming, we can derive an equivalent *envelopment form* of the above problem, which can be formulated as follows:

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[2] If (u*, v*) is an optimal solution, then (*a*u*, *a*v*) is also optimal for *a*>0 [Cooper et al, 2004].

$$
\begin{aligned}
&\min \theta \\
&s.t. \qquad \sum_{j=1}^{n} x_{ij}\lambda_j \le \theta x_{ic}, \quad i = 1,\cdots,m \\
&\qquad\qquad \sum_{j=1}^{n} y_{rj}\lambda_j \ge y_{rc}, \quad r = 1,\cdots,s \\
&\qquad\qquad \lambda_j \ge 0, \quad j = 1,\cdots,n
\end{aligned}
\tag{3}
$$

where θ is a scalar and λ is a n×1 nonnegative vector of constants.

Conceptually, the dual attempts to construct for each country a hypothetical composite unit (HCU) that outperforms it. The composite unit produces outputs that are at least equal to the corresponding outputs of a particular country *c* and consumes at most a proportion θ of its inputs ($0 < \theta \le 1$). The intensity factor θ can thus be used to determine the minimum amount by which the inputs must be proportionally reduced for the country *c* to become efficient, and its value will be the same as *h* calculated in (2) with a value of one indicating a best-performing country. Moreover, for those countries that contribute to the construction of the HCU, they will have non-zero dual weights, i.e., λ, and make up the reference set for country *c* [El-Mahgary et al., 1995].

5 APPLICATION AND RESULTS

In this study, the DEA approach is employed to show an overall road safety picture of a set of European countries, and to further assess whether the road safety outcomes registered in a country correspond to the numbers that can be expected based on the level of exposure. In doing so, we first collected data for the 27 EU countries in terms of three common measures of exposure to risk, i.e., the number of inhabitants, passenger cars and passenger-kilometres travelled, as well as the number of road fatalities in 2007 [EC, 2009]. Unfortunately, the initial examination revealed the very distinct nature of the data for Malta and consequently it was decided to eliminate this outlier and only consider 26 EU countries.

Furthermore, as opposed to other fields such as economics, in this case, we want the output---road safety fatalities---to be as low as possible. Hence, the ratio of the weighted input (or exposure) to the weighted output (or fatalities) will be maximized. The overall optimal road safety efficiency score for each of the 26 EU countries from either the primal or the dual DEA model is presented in Table 2.

Table 2: Optimal road safety efficiency scores of the 26 EU countries based on DEA

Country	Efficiency score
NL	1
UK	1
SE	0.9605
DE	0.8232
FI	0.7490
LU	0.7273
FR	0.7095
IT	0.7020
DK	0.6277

AT	0.5930
IE	0.5780
ES	0.5415
BE	0.4801
PT	0.4714
CY	0.4271
SK	0.3726
CZ	0.3663
SI	0.3554
HU	0.3533
RO	0.3338
BG	0.3295
EL	0.3066
EE	0.2963
PL	0.2955
LT	0.2353
LV	0.2351

It can be seen that the Netherlands and United Kingdom are the only two best-performing countries since they obtain the optimal efficiency score of one, which means that they are at the top of the countries' performance ranking, while the remaining 24 countries (obtaining values less than one) are considered to be underperforming and can be ranked by their scores directly. Moreover, comparing the ranking result with the ones in Table 1, which are based on the three risk indicators separately, we find that the result from the DEA model gives us a global view on the country's road safety efficiency by taking all three aspects of exposure into account, and yet it is not the simple average of those three rankings.

To better understand the computational process leading to the efficiency scores presented in Table 2, and especially the reasons why the 24 underperforming countries are unable to obtain a value of one, we can further explore the mechanism of the primal and dual DEA approach, respectively. Theoretically, the primal DEA model is to choose the best possible input and output weights under the imposed restrictions to maximize the efficiency score of a certain country. If the optimal weights of a country *A* under study do not result in a value of one for this country but cause the weighted score of another country *B* in the data set to become one, then the model stops. This implies that country *B* is characterized by a lower risk than country *A* with respect to at least one of the exposure aspects since the efficiency score of *B* is relatively higher with the same set of weights. Therefore, country *A* could take country *B* as an example for improving its road safety performance. From the dual DEA model's point of view, the dual weights, i.e., λ, can be viewed as indicating the amount of technical weight that is attributed by each benchmark country in the construction of an efficient HCU. In other words, the countries with non-zero dual weights make up the reference set for the country under study. Using this principle, the reference sets and dual weights of all 24 underperforming countries are indicated in the second and third column of Table 3. In the remaining two columns, the registered number of fatalities in 2007 and the proposed targets are presented for these countries, which will be discussed below.

Table 3: Reference sets and targets for the 24 underperforming countries

Country	Ordered reference set	Dual weights (λ)	Fatalities in 2007	Target
BE	{NL, UK}	0.284, 0.102	1067	512.22
BG	{NL}	0.468	1006	331.52
CZ	{NL}	0.631	1221	447.26
DK	{NL, UK}	0.169, 0.044	406	254.83
DE	{NL, UK}	4.268, 0.343	4949	4073.92
EE	{NL}	0.082	196	58.07
IE	{NL, UK}	0.205, 0.016	338	195.36
EL	{NL}	0.683	1580	484.42
ES	{NL}	2.918	3821	2068.94
FR	{UK, NL}	0.973, 0.426	4620	3277.83
IT	{NL, UK}	2.383, 0.625	5131	3602.25
CY	{NL}	0.054	89	38.01
LV	{NL}	0.139	419	98.51
LT	{UK}	0.057	739	173.88
LU	{NL, UK}	0.037, 0.002	43	31.27
HU	{NL}	0.614	1232	435.21
AT	{NL}	0.578	691	409.75
PL	{NL}	2.327	5583	1649.86
PT	{NL}	0.648	974	459.13
RO	{NL}	1.315	2794	932.55
SI	{ NL, UK}	0.028, 0.027	292	103.77
SK	{NL}	0.329	627	233.60
FI	{UK}	0.093	380	284.61
SE	{UK, NL}	0.135, 0.055	471	452.42

Firstly, it can be seen that the reference set for each underperforming country is solely comprised of one or both of the two best-performing countries, i.e., the Netherlands and United Kingdom. Totally, 22 times NL acts as a benchmark country while 11 times UK.

Moreover, since the value of the dual weight points out the extent to which each benchmark country contributes to the definition of the HCU for each underperforming country, it enables us to rank the benchmark countries in terms of their relative importance. Taking Belgium as an example, the dual weight of NL (0.284) is more than twice as large as that of UK (0.102) implying that NL plays a stronger role in determining the ideal performance of Belgium.

More importantly, the constructed HCU offers information for setting a challenging target for each underperforming country in order to become efficient. In other words, for each underperforming country, a quantitative road safety target can be formulated by learning from its benchmarks, using the following formula:

$$T_j = \lambda_{NL} F_{NL} + \lambda_{UK} F_{UK} \quad j = 1, \cdots n \tag{4}$$

where T_j denotes the target number of fatalities for the *j*th underperforming country. F_{NL} and F_{UK} are the number of fatalities in NL and UK in 2007, which were 709 and 3058, respectively. Thus, for the case of Belgium, its target number of fatalities can be calculated as:

$0.2838 \times 709 + 0.1017 \times 3058 = 512.22$. In other words, Belgium is currently only half way (compared to its current figure of 1067) to belong to the group of best-performing countries in the EU. Furthermore, for the whole EU Member States, the overall target (summing up the target values of the 24 EU countries in Table 4 together with the current values of NL, UK and MT) would be 24,388, while its figure in 2007 was 42,448, which means that it could be reduced 42.55% if all countries were as efficient as NL and UK. Therefore, greater efforts are needed, at both the European and national levels.

6 CONCLUSION

Road traffic injuries and fatalities will continue to be one of the most serious public health issues within the next decade. In order to make progress in road safety, countries need to evaluate their own safety performance, compare it with that of other countries, and further learn from those best-performing ones by indicating challenging quantitative targets and action programmes for themselves. In this paper, the research on data envelopment analysis is presented to measure and compare the efficiency of 26 EU countries by taking three main risk indicators (i.e., the number of fatalities per million inhabitants, the number of fatalities per million passenger cars, and the number of fatalities per 10 billion passenger-kilometres travelled) into account simultaneously. Applying the model linking input (or exposure to risk) and output (or the number of fatalities), an overall optimal road safety efficiency score is computed for each country considering the information on all other countries in the data set. Moreover, based on the model results, best-performing and underperforming countries could be identified, and benchmarks for those underperforming ones indicated. More importantly, the extent to which the benchmarks could be learned from has been specified, and a challenging target or improvement potential has been given for each underperforming country.

In the future, more aspects could be investigated. Firstly, other inputs or outputs could be used to describe road safety, e.g., safety performance indicators and policy performance indicators [Wegman et al., 2008; Tingvall et al., 2010], which could enable policymakers to prioritize their investments to enhance the level of road safety. Secondly, uncertainty and sensitivity analysis should be conducted to reveal the impact of a change in data set, for example, regarding input/output specification, sample size, and data quality. Thirdly, DEA is suitable for country comparisons over time as well, which makes it possible to set quantitative targets for the benchmark countries since the best performing country in one year may not be best the next year. Moreover, for the most underperforming countries, rather than only specifying one single, probably hard to achieve target, several more realistic ones, especially for short or medium terms, should be taken into account, which can be realized by using the categorical DEA model. Finally, from the road safety policy point of view, we should keep in mind that setting targets does not guarantee their achievement unless keeping adequate political ambition, effective strategies, sufficient allocation of resources, successful implementation, and persistent monitoring and evaluation as an ongoing process throughout the whole target period.

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