

## STRATEGIES FOR DEVELOPING WIM CONTROL INFRASTRUCTURE FROM AN ECONOMIC PERSPECTIVE

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**Purpose:** The main objective of the study is to evaluate the economic effectiveness of developing a modern control infrastructure in Poland, using the example of an automated weigh-in-motion (WIM) system. Specifically, the paper aims to identify the optimal investment implementation strategy while taking into account the benefits of infrastructure and partly social.

**Design/methodology/approach:** Based on a review of the literature and data on the investment costs of a potential automatic weighing system for vehicles in motion, a cost-effectiveness analysis was performed using the extended NPV focusing on infrastructure and safety externalities model for various implementation strategies for WIM stations in Poland. The model covered 15 years, for which different installation strategies were examined at different time intervals and at the installation level, taking into account additional potential costs and savings from using the WIM system.

**Findings:** Implementing a WIM system in Poland, with 300 locations, can be feasible from both an economic and partial social perspective focused on safety and infrastructure. A key factor that influences investment is the timing of the investment. Implementation strategies that generate or distribute WIM station rates over the study period yield significantly lower NPVs than phased implementation strategies (E and F) provide the highest economic efficiency.

**Research limitations/implications:** The analysis considered only measurable social outcomes, such as reduced road accidents. Other outcomes, such as reduced pollution and noise, were described qualitatively. Further research should also consider these evolving parameters, as well as the legal, technological, and organisational conditions that may impact the system's long-term functioning.

**Originality/value:** The research shows that the development of the control infrastructure with a modern vehicle weighing system in Poland can bring potential benefits to the country's transport system both economically and socially.

**Keywords:** automatic vehicle weighing system, WIM, control infrastructure, efficiency of road investments.

**Category of the paper:** empirical surveys, scientific surveys.

## 1. Introduction

The development of road infrastructure in Poland, particularly in the context of growing heavy-duty vehicle traffic, requires the implementation of modern control solutions that will enable effective enforcement of regulations concerning the maximum allowed weight of vehicles. Therefore, the development of effective control infrastructure solutions for the identification of overloaded vehicles in road traffic is one of the possible ways to reduce the negative impact of heavy and overloaded vehicles on road durability and road safety (Ghosn, 2010). However, the current selective vehicle weighing control system in Poland is not sufficient to effectively identify all overloaded vehicles travelling on national roads (Ossowski, Burnos, 2015). An effective solution may be to implement the concept of automatic weighing of vehicles in motion. The Weigh-in-Motion (WIM) system responds to these needs by enabling the identification of overloaded vehicles without the need to stop them. The implementation of such a system not only increases the effectiveness of controls but also contributes to reducing road surface degradation and improving road safety (Ryś, Judycki, Jaskuła, 2014).

WIM technology enables continuous monitoring of loads generated by heavy goods vehicles and automatic recording of violations, which contributes to better maintenance of road infrastructure and increased traffic safety (Ryś, Judycki, Jaskuła, 2014). The automatic weighing system for vehicles in motion significantly improves the effectiveness of vehicle weight control by focusing exclusively on identifying suspicious cases (Sujon, Dai, 2021). At the same time, the installation of this type of system involves high investment costs, especially in the initial phase of implementation (Sochoń, Siedlanowska-Chałuda, 2014). However, neglect in this area can result in accelerated infrastructure degradation through faster wear and tear, and thus an increase in road safety risks (Sokołowicz, Przygodzki, 2016). Therefore, the aim of the study was to assess the economic efficiency of the development of modern control infrastructure in Poland using the example of an automatic weigh-in-motion (WIM) system.

## 2. Literature review

### 2.1. Impact of heavy vehicle overloads on road infrastructure

Deterioration of the road surface caused by excessive traffic of overloaded heavy-duty vehicles is one of the most serious operational problems of the transport infrastructure. The impact of heavy vehicles on the road surface is well described by the so-called fourth power law, according to which the impact of vehicle axle load on the surface increases exponentially (Cho, Lakatos, 2022). This means that even a slight exceedance of the permissible gross vehicle

weight can lead to a drastic increase in the degree of road surface degradation (Ryguła et al., 2020; Dzienis, Karkowski, 2010). An OECD report (2011) also confirms that exceeding the permissible weight of a heavy goods vehicle by 50% increases the destructive effect by 400% and exceeding it by 100% increases it by up to 16 times. These data have a direct impact on the frequency of partial and periodic repairs, as well as on the durability of road structures, which directly into increased road infrastructure maintenance costs. In regions with high heavy truck traffic, especially in locations with high average annual and daily traffic volumes, infrastructure is subject to faster wear and tear, which generates higher maintenance costs.

Overloaded vehicles affect not only the technical condition of the road surface, but also road safety elements such as energy-absorbing barriers, horizontal and vertical markings, and signaling devices (Ryś, 2012). Investments in the development of the control infrastructure, which also includes a modern vehicle weighing system, can significantly reduce the negative impact of overloaded heavy vehicles on the road surface (Ślusarczyk et al., 2025). The implementation of a weight-in-motion (WIM) system allows for the identification of overloaded trucks in real time. The implementation of this type of investment project in the development of road control infrastructure enables more efficient and effective exclusion of overloaded vehicles from traffic, thereby reducing their negative impact on road surfaces. Effective overload control has been shown to extend the life of the road surface by up to 30-40%, which translates into real savings for the road administrator (Mulyono et al., 2010; Nowak, 2015). Also “WIM enables the transfer of vehicle load data, allows data to be transferred when limits are exceeded and can send a message for more effective preventive actions” (Chład, 2024).

## **2.2. Social costs associated with heavy overloaded vehicles**

In addition to its control function, the WIM system also plays an important role in reducing the social costs associated with road transport. Overloaded vehicles are statistically more likely to be involved in road accidents, which translates into a higher risk of accidents, a greater number of victims, and higher costs of treatment, rehabilitation, and material losses (Taylor, Bergan, Lindgren, 2000). The GDDKiA (2024) report clearly indicates that locations with heavy truck traffic are characterized by a higher accident rate. The available studies do not provide an exact figure for the proportion of overloaded trucks involved in road accidents, but the available data allow general conclusions to be drawn. However, it is known that combination trucks with additional trailers are involved in approximately 1.7% of fatal accidents (U.S. Department of Transportation, 2021). According to statistics, in China, 80% of accidents on mountain roads involving trucks are due to their overload (Wen et al., 2022). Furthermore, of all heavy trucks involved in accidents, only 0.08% are overloaded or improperly loaded, and 0.43% of vehicles carry oversized loads (Green et al., 2020). Overloaded trucks are estimated to account for 0.2% of all trucks involved in road accidents (US Department of Transportation, 2021). Furthermore, the social costs associated with

accidents are classified as external costs, which are not borne directly by the perpetrators, but by society as a whole (JASPERS, 2023). Taking these costs into account in the investment effectiveness analysis allows a more complete understanding of the benefits of implementing a WIM system. Reducing the number of overloaded vehicles leads to a decrease in the number of accidents, which translates into a lower burden on the health system, lower material losses, and an improvement in the quality of life of residents. The WIM system also has a preventive effect: drivers' awareness of the possibility of automatic vehicle weight control influences their behaviour, leading to greater compliance with regulations. Although difficult to measure directly, is an important factor in improving safety and reducing social costs.

### **2.3. Assessment of the profitability of investments in control infrastructure**

The development of road infrastructure is based on numerous EU and national investment projects aimed at implementing specific measures in the country's transport network, primarily leading to financial, social, or infrastructural benefits (Domański, 2009). Infrastructure investments require not only significant capital expenditure but also appropriate organizational, technical, and legislative support. In the case of public projects such as WIM, it is also important to take into account social aspects such as the impact on road safety, the quality of life of residents, and the durability of infrastructure. These projects are long-term in nature and their effects are spread over time, which requires the use of appropriate methods of profitability assessment, taking into account the volatility of money value and the impact of external factors (Ślusarczyk, Grondys, 2025).

The evaluation of investment profitability is a key element of the decision-making process, allowing rational allocation of resources and minimisation of financial risk. Some of the most common tools are NPV (Net Present Value), IRR (Internal Rate of Return), payback period, sensitivity analysis, and scenario analysis (Zadora, 2013; Kozłowski, 2012). The NPV indicator allows the net value of an investment to be determined by discounting future cash flows to their present value. It takes into account the principle of the change in the value of money over time, which is particularly important in the case of long-term projects such as investments in road infrastructure. Furthermore, the use of the NPV method to assess the profitability of implementing a WIM system allows for the consideration of both initial costs and benefits spread over many years. This approach is also justified by the nature of the investment, in which cash flows are irregular and depend on many external factors (Uyar, 2009). In addition, the analysis of the profitability of investments using the NPV method allows for the consideration of not only financial aspects, but also social and environmental aspects that arise in the case of WIM system implementation. At the same time, due to the need to analyse other factors as well, traditional methods of profitability assessment, focusing exclusively on financial flows, that is, the NPV method, do not provide a complete picture of the effectiveness of infrastructure investments (Mielcarz, Paszczyk, 2013).

In the broader context of cost-effectiveness, extended models such as the eNPV method are increasingly being used, which allow for the inclusion of costs and benefits that cannot be directly measured in monetary terms, e.g., reduction in the number of road accidents, improvement in air quality, or noise reduction. The NPV method is an extension of the classic cost-benefit analysis model, taking into account social and environmental effects that are important in the case of public investments. In the context of the WIM system, the use of the eNPV model is particularly justified but requires quantified social and environmental data. The WIM system not only improves the effectiveness of overload control, but also reduces the social costs associated with infrastructure degradation and road accidents. Taking these effects into account in the economic analysis allows for a more complete assessment of the cost-effectiveness of the investment and a better justification for its implementation within the country's transport policy. At the same time, due to the limited possibilities of calculating environmental costs, the study mainly refers to the economic effects of the investment implementation, taking into account only selected social effects.

### **3. Research methodology**

#### **3.1. Research Objective and research method**

This article presents an analysis of the development strategy for the WIM control infrastructure in Poland from an economic perspective. Five implementation options were evaluated, differing in terms of the pace and distribution of investments over time. The objective of the study was to assess the economic efficiency of the development of modern control infrastructure in Poland on the example of an automatic weigh-in motion (WIM) system, which will ensure an optimal return on investment while taking into account social and infrastructural benefits. The study assumes the implementation of the WIM system in Poland.

Due to the lack of market valuations of all external costs, the model takes into account quantifiable social benefits in terms of road safety (accident reduction), omitting quantitative environmental aspects (noise, emissions), which are described only qualitatively. Therefore the extended NPV (socio-economic NPV approach) focusing on infrastructure and safety externalities model for various implementation strategies for WIM stations in Poland was used to assess the project's profitability, taking into account only some social effects. The analysis took into account both the revenues generated by the system and the investment and operating costs. Revenues included income from administrative penalties, savings resulting from a reduction in the number of road accidents, and savings from deferred infrastructure repairs. The costs included investment outlays, the operating costs of the WIM stations, and the operating costs of the system headquarters. The profitability assessment also took into

account technical parameters such as the type of support structure, the length of the station, drainage requirements, and the availability of energy infrastructure, which directly affect investment costs.

The literature indicates that optimising these parameters can lead to significant savings, especially in the case of large infrastructure projects (OECD, 2011). Based on the standard results of infrastructure investments in Poland, taking into account the cost of capital, investment risk, and the share of public financing, the model assumes a discount rate of 6% over a 15-year time horizon, which corresponds to the expected life expectancy of the investment. According to the assumptions of the NPV model, the study covered specific categories of potential expenditures and revenues related to the implementation of the WIM control infrastructure (Table 1).

**Table 1.**

*Types of potential expenditures and revenues related to the implementation of the WIM system*

Investment income	Investment costs	Operating costs
Revenue from administrative penalties for exceeding the permissible gross vehicle weight	Expenditures for the construction of WIM stations	Ongoing maintenance of WIM stations (calibration, data transmission, legalization)
Savings resulting from a reduction in the number of road accidents involving overloaded vehicles.	Purchase of servers, software, and office equipment for the system headquarters	System headquarters operating costs (server room, Internet connections, IT support, management)
Savings from deferred road infrastructure repairs.	Costs of modernisation and maintenance of control infrastructure in subsequent years	

Source: own research.

### 3.2. Scope of input data

The input data for the model were developed on the basis of a detailed analysis of 1825 road sections in Poland, from which 300 locations with the greatest potential for economic efficiency were selected. The location of the WIM stations and the technical parameters of the infrastructure were key in evaluating the effectiveness of the system. The selection of appropriate measurement points took into account traffic intensity, the share of heavy-duty vehicles in traffic, the number of lanes, the availability of power connections, and the possibility of reorganising traffic during installation. Additionally, the number of lanes, the number of road accidents, the unit costs of repairs, and the technical parameters of the infrastructure were taken into account. Based on these data, locations were selected using the TOPSIS multi-criteria method, taking into account, among other things, SDRR (average daily annual traffic), SC (heavy goods vehicle traffic), and SCP (heavy goods vehicle traffic with trailers and semi-trailers) indicators. The developed location selection algorithm allowed for the creation of a ranking of measurement points, which formed the basis for a further detailed analysis of implementation strategies. The model assumes a decreasing share of overloaded vehicles in subsequent years of the system's operation, which affects the value of savings.

### 3.3. Assumptions of the implementation strategy model

The objective of this study is to maximize the economic net present value subject to a 15-year planning horizon and a 6% discount rate. The definition of possible implementation strategies for the WIM system is based on the assumption that 300 vehicle weighing stations will be installed over a 15-year period. This means that regardless of the implementation option adopted, the total number of stations installed during the analysed period remains constant, while the decision variable is its distribution over time — both in terms of the number of stations installed in individual years and the pace of investment. This approach allows for a comparative analysis of different implementation scenarios, taking into account the impact of the pace of investment on the economic value of the project. In particular, it allows for an assessment of the extent to which the intensity of investment in the first years of the system's operation affects the net present value (NPV). Each strategy has been designed to reflect realistic organisational and budgetary possibilities, while at the same time allowing for the identification of the optimal implementation option from the point of view of economic efficiency.

### 3.4. The investments in various implementation strategies

The calculation model was developed in the form of an active proprietary simulation model, enabling the simulation of NPV values for various implementation strategies. The model allows for the analysis of the profitability of system implementation in various time and investment variants. Six variants of the strategy were considered, differing in the number of stations implemented in individual years (Table 2).

**Table 2.**

*Distribution of WIM station installations over time*

Year of investment	Identification of implementation strategies					
	A	B	C	D	E	F
Number of installations						
1	100	300	100	150	25	5
2	0	0	100	0	25	10
3	0	0	100	0	25	15
4	200	0	0	0	0	25
5	0	0	0	0	25	40
6	0	0	0	0	25	0
7	0	0	0	0	25	0
8	0	0	0	150	0	25
9	0	0	0	0	25	35
10	0	0	0	0	25	45
11	0	0	0	0	25	0
12	0	0	0	0	0	0
13	0	0	0	0	25	15
14	0	0	0	0	25	35
15	0	0	0	0	25	50

Source: own research.

Based on the ranking of the WIM station locations, they were then divided into four percentiles, each containing 75 stations. This division was used to develop a simulation of the NPV value in the adopted strategic variants, assuming the construction of 25 to 300 stations over 15 years. This assumption is intended to show changes in the NPV value for twelve different ranges specifying the construction of the number of WIM stations.

### 3.5. Economic profitability results for individual implementation strategies

The NPV was then calculated for each strategy, taking into account revenues, costs, and the discount rate. Revenues included the estimated decreasing value of administrative penalties for vehicle overloading, potential savings from the reduction of accidents involving heavily overloaded vehicles, and the amount of savings that could be generated from deferred road repairs. The costs included the costs of operating the stations, managing the system, and the capital expenditure associated with building the system. The results of the cost-effectiveness assessment of individual strategies A, B, C, D, E, and F for the 12 ranked location ranges are presented in Table 3.

**Table 3.**

*NPV calculation results for the adopted implementation strategies [PLN]*

<b>Range</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Number of stations</b>	<b>25</b>	<b>50</b>	<b>75</b>	<b>100</b>	<b>125</b>	<b>150</b>
Strategy A	-52 105 219	-31 458 267	-24 073 032	-26 068 772	-20 083 725	-24 301 512
Strategy B	-52 105 219	-31 458 267	-24 073 032	-26 068 772	-34 566 799	-53 267 659
Strategy C	-52 105 219	-31 458 267	-24 073 032	-26 068 772	-29 455 233	-43 044 527
Strategy D	-52 105 219	-31 458 267	-24 073 032	-26 068 772	-34 566 799	-53 267 659
Strategy E	-52 105 219	-26 346 701	-9 027 668	7 751 434	22 077 090	30 019 571
Strategy F	-46 087 07	-11 866 90	13 434 821	32 508 314	54 936 978	69 882 395
<b>Range</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>
<b>Number of stations</b>	<b>175</b>	<b>200</b>	<b>225</b>	<b>250</b>	<b>275</b>	<b>300</b>
Strategy A	-3 591 524	12 765 888	15 787 791	30 178 722	65 084 996	<b>119 573 631</b>
Strategy B	-47 040 746	-45 166 406	-56 627 577	-56 719 720	-36 296 520	<b>3 709 041</b>
Strategy C	-31 706 047	-24 720 142	-26 247 515	-16 405 859	13 951 138	<b>63 890 498</b>
Strategy D	-16 793 951	15 327 181	34 112 804	64 267 456	114 937 450	<b>185 189 805</b>
Strategy E	69 892 762	108 620 438	137 038 133	183274118	266 701 467	<b>357 069 668</b>
Strategy F	112 321 234	151 048 910	192 586 276	255498283	326 284 122	<b>416 652 323</b>

Source: own research.

The determined NPV values should be interpreted in terms of the WIM system as a whole for 300 stations. The results clearly show that for each of the adopted strategies, the NPV value is greater than zero (range 12 is the summary of the extended NPV value for all 300 stations), but with a clear difference in its value. The strategy variants assume specific numbers of WIM stations to be implemented in a given year of the investment. The appearance of negative values suggests low profitability of the investment in the initial stages. Visible positive values start at 75 stations and reflect the positive end result for each strategy at different stages of system implementation, depending on the number of weighing stations in operation.

The simulation results showed significant differences in the extended NPV values between the strategies. Strategies spread over time (E and F) achieved the highest NPV values, indicating their greatest economic efficiency. The intensive strategies (B and C), despite their rapid implementation, were characterised by lower profitability due to high investment costs in a short period of time. The analysis showed that the break-even point (i.e., the point at which NPV becomes positive) varies depending on the strategy:

- Strategy A: positive NPV with the implementation of >175 stations.
- Strategy B: positive NPV only with the full implementation of 300 stations.
- Strategy C: positive NPV with 250 stations.
- Strategy D: positive NPV with 175-200 stations.
- Strategy E: positive NPV with as few as 75-100 stations.
- Strategy F: positive NPV with as few as 75 stations.

These results indicate that strategies with lower investment intensity in the initial years allow for faster achievement of a positive NPV, which is beneficial from the point of view of investment risk management.

#### **4. Conclusions**

The analysis of the economic efficiency of implementing a weigh-in-motion (WIM) system in Poland allows us to draw clear conclusions regarding the validity of the investment and the optimal strategies for its implementation. Although the model adopts a societal perspective, it is limited to costs related to the safety of infrastructure users. Environmental externalities, such as noise and emission reductions, are not quantified in the model, but only qualitatively. This means that the estimated quantitative effects of the extended NPV represent a lower bound on the system's possible societal benefits. The results obtained using the extended NPV focusing on infrastructure and safety externalities calculation model indicate that the implementation of the WIM system on a national scale, covering 300 locations, is a profitable undertaking from both an economic and social point of view.

The main factor influencing the effectiveness of the investment turned out to be the distribution of expenditure over time. Implementation strategies that assumed an even or staggered pace of WIM station installation showed significantly higher NPV values than intensive variants implemented in the short term. Strategies E and F proved particularly advantageous, as they implemented the system in stages, taking into account investment interruptions and fluctuations in the number of stations installed in individual years. These scenarios were identified as optimal according to the NPV maximization criterion, assuming 6% discount rate and the lack of full quantification of benefits (e.g., environmental). First, investment expenditures incurred in later years (strategies E and F) have a significantly

lower present value than the same expenditures incurred at the beginning (short-term strategies). On the other hand, these strategies do not take into account quantified environmental benefits. It can be assumed that once they are incorporated, the advantage of short-term strategies (faster emission reductions by eliminating overloaded vehicles) will be greater.

From a public interest point of view, the implementation of the investment is also strongly justified by the scale of potential social and environmental benefits. Reducing the number of road accidents involving overloaded vehicles will reduce the costs of treating victims, limit material losses, and improve road safety, which has a measurable impact on the quality of life of residents and the functioning of the transport system.

At the same time, the effective implementation of the WIM system in Poland should be carried out in stages, taking into account the locations with the highest efficiency and using a strategy of installing weighing stations spread out over time. This approach to investment allows for optimal economic results, minimisation of investment risk, and maximization of social benefits. The study has certain limitations that should be considered in future research. The analysis only took into account measurable social effects, such as a reduction in the number of road accidents. Other effects, such as a reduction in pollutant emissions or noise, were described only qualitatively. At the same time, further studies should take into account changing parameters, as well as legal, technological, and organisational conditions that may affect the functioning of the system in the long term.

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