WIM PLACEMENT ON ROAD NETWORKS: OPTIMIZATION MODELS AND A PROPOSED DEPLOYMENT PROCESS


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Abstract

Overloaded vehicles pose a significant threat to road safety and infrastructure sustainability. Weigh-In-Motion (WIM) systems have been developed to address this issue by providing real-time weight measurements of vehicles without requiring them to stop. However, the effectiveness of WIM networks depends on the optimal placement of the systems across the road network. This is because carriers that travel overweight often do so on purpose to seek economic gains and will actively seek alternatives routes to avoid passing through WIM stations if possible. This paper focuses on this issue by presenting a review of computational optimization models that address the problem of locating WIM stations on a road network so that no escape routes are left, including a case study of a practical application of one of the models to gain insights into their use and the results obtained. Although essential to solve the evasion problem, optimization models are recognized as only a part of a comprehensive implementation of a WIM network, and thus an overall, well-rounded WIM deployment strategy is proposed that consists of five main phases: Initiation, Planning, Confirmation, Deployment, and Evaluation. Ultimately, this paper aims to serve as a starting point for decision makers to build comprehensive deployment plans for WIM networks.

Keywords: Road Networks, Weigh-In-Motion, Weight Enforcement, WIM systems, Equipment Placement, Deployment, Planning, Strategy.

1. Introduction

Weight enforcement is a critical issue for any organization responsible for maintaining road networks. The challenge is that freight carriers tend to be motivated to overload their trucks beyond legal limits, as it generates economic benefits for them (Ghisolfi *et al.*, 2019). Furthermore, carriers may choose to avoid weight enforcement by taking longer routes where vehicles won't be weighed. Overweight trucks cause multiple issues for the road network, including safety risks when they cannot manoeuvre correctly, slower traffic on ramps, and longer braking distances, which raises the likelihood of severe accidents. Additionally, carriers that overload their trucks have an unfair advantage over competitors who follow the law by being able to offer lower prices. Lastly, overweight trucks cause exponential additional damage to the road pavements and bridges, which can result in pavement/bridge failure before reaching the designed lifespan. As a result, the overall cost of not controlling weight will far exceed the investment required to create efficient weight enforcement networks.

The recent advancements in Weigh-In-Motion (WIM) systems have made weight enforcement even more accessible and efficient. Nowadays, high-speed weighing is a reality, and many countries worldwide are discussing the implementation of direct weight enforcement with high-speed WIM. This means that carriers can be fined automatically at high speeds without the need to stop the trucks and use higher precision scales. Previously, weight enforcement required dedicated infrastructure where vehicles would be weighed either statically or at low speeds and would require an area to park. However, with WIM, weight control is automatic, and no land expropriation is necessary. This makes it easier for road maintenance entities to install new weight enforcement points and monitor more sections of the network. The placement of WIM stations across the network has become a more dynamic task, with criteria other than the availability and price of land becoming more relevant when choosing where to place them.

There are several factors to consider when deciding where to place WIM stations. However, the issue of enforcement evasion is crucial. Experience has shown that some freight carriers will try to avoid weighing stations by changing their routes, which can undermine the effectiveness of the enforcement system (Franceschi *et al.*, 2020). Controlling evasion is challenging because traffic demand varies significantly across the road network. To address this problem, mathematical optimization formulations such as the Evasive Flow Capture Problem (Marković, Ryzhov and Schonfeld, 2015) can be helpful. This approach aims to maximize the capture of evasive vehicle flows by installing enforcement equipment in areas where drivers cannot avoid them. This is achieved through a mathematical optimization process that considers network topology, as well as flow characteristics like origins, destinations, and volumes. Typically, these models use graphs with nodes and links to represent the road network and the flow volumes of each origin-destination pair as input. They then identify the most suitable links to capture evasive flows. Some models incorporate a maximum distance that carriers will travel to avoid enforcement, while others adopt a "pessimistic" approach that assumes drivers choose roads with the highest damage costs (Bogyrbayeva and Kwon, 2021).

When considering the implementation of WIM systems across regional or national road networks, a strategic approach is essential for achieving maximum effectiveness. This involves carefully planning the deployment of WIM systems based on data collection and statistical analyses. While optimization models are a useful tool in this process, they may not be sufficient on their own to determine the best placement of WIM systems. To create an effective enforcement network, WIM deployment strategies must consider multiple criteria and the entire decision-making process. While they are only one part of a comprehensive approach of WIM network planning, optimization models play a critical role in ensuring protection against enforcement evasion. Therefore, the objective of this paper is to explore optimization models and theories for determining the best locations for weighing equipment in road networks. Specifically, the paper will focus on operational research models that aim to maximize flow capture. Additionally, the paper will provide a discussion on the broader WIM deployment process and introduce a proposed model for this process.

1.1. Optimization models

An optimization model is a mathematical representation of a real-world problem that seeks to find the best possible solution according to an expressed goal. The model is made up of several key components, including decision variables, objective function, constraints, parameters, and assumptions. The decision variables are the values that the model seeks to optimize, while the objective function defines the goal of the optimization problem. Constraints place restrictions on the values that the decision variables can take, and parameters are fixed values used in the objective function or constraints. Assumptions are simplifying assumptions that are made to make the optimization problem more tractable. Finally, the solution methodology refers to the algorithms and techniques used to solve the optimization problem. By taking all these components into account, an optimization model can enable difficult solutions to be found.

In the context of determining WIM locations, a common approach is to first establish parameters that represent the road network as a graph. This involves defining several sets with specific meanings, including nodes, links, traffic flows (with origins and destinations specified), and traffic volumes. Next, a set of decision variables is created to correspond with the parameters that represent the network. These decision variables are typically binary and associated with different links on the network, with values indicating whether a WIM station will be placed on that link or not. The model is then subject to constraints, such as the total number of WIM stations, which can be formulated as a restriction on the sum of all binary decision variables to a certain constant parameter. Restrictions play a crucial role in ensuring that the mathematical model accurately reflects the real-world scenario. For example, flow conservation restrictions ensure that all paths considered are continuous along the graph and that all links are appropriately connected, thereby ensuring that the paths are valid. Once all parameters, objective functions, and constraints are defined, the model can be said to be fully formulated.

The term “bilevel” optimization refers to a type of mathematical model that consists of two levels of optimization problems, one nested within the other. The upper level represents a decision-maker who seeks to optimize a certain objective function subject to a set of constraints. The lower level, on the other hand, represents the response of another decision-maker to the choices made by the upper-level decision-maker. This response is modelled as a lower-level optimization problem that depends on the upper-level decision variables. Bilevel models are commonly used to model situations where there are two decision-makers who each have their own objectives and constraints, but where the decisions made by one decision-maker affect the decisions that the other decision-maker can make. Bilevel models are often difficult to solve because the constraints and objective functions of the lower-level problem depend on the upper-level decision variables.

In the case of WIM location optimization, bilevel models are frequently used to capture the decision-making process of the road maintenance entity regarding the placement of WIM stations on the network (upper level). At the lower level, the overloading freight carriers make decisions on their route based on the current WIM station placement to avoid them. This dynamic presents a challenge for modelling and optimization, as it can be too complex to model directly. As a result, researchers have proposed various approaches to enable the efficient computational solution of these bilevel problems.

2. Approaches for WIM Equipment Location in Literature

In Table 1, we have compiled a list of relevant papers in the literature that contain models, formulations, and theories applicable to the computational optimization of WIM station locations over road networks. Our review primarily focused on mathematical optimization formulations explicitly designed for WIM location, although other studies where WIM placement was studied by other methods were also considered. For reference, we have also included a brief description of the methods utilized in each of the papers.

Table 1 – Approaches in literature for WIM equipment location

Reference	**Method used for WIM location**
Ammarapala *et al.* (2013)	Analytic Hierarchic Process
Arslan *et al.* (2018)	Bilevel optimization model with a custom Branch and Cut algorithm
Bogurbayea and Kwon (2021)	Pessimistic bilevel optimization model with cut plan algorithm
Hooshmand and Mirhassani (2018)	Bilevel optimization model
Jinyu, Xu and Zhongzhen (2020)	Analytic Hierarchic Process
Kulović *et al.* (2018)	Deterministic flow interception model
Lu *et al.* (2018)	Bilevel optimization model with heuristic solution
Mahmoudabadi and Seyedhosseini (2013)	Bilevel optimization model and shortest path algorithm
Marković, Ryzhov and Schonfeld (2015)	Bilevel optimization model and lagrangian heuristic
Marković, Ryzhov and Schonfeld (2017)	Bilevel optimization model with an algorithm based on lagrangian relaxation
Rygula, Brzozowski and Maczyński (2020)	Statistical analysis of weight station data
Sayyady *et al.* (2013)	Lagrangian Heuristic Algorithm

All the papers listed provide different approaches for choosing WIM station locations, but one noteworthy formulation for the specific problem of enforcement evasion is proposed by Marković, Ryzhov, and Schonfeld (2015). They use a bilevel optimization problem, where the upper level represents WIM system planners who choose where to install WIM stations, and the lower level represents carriers' decisions on which routes to take. The goal of the upper-level decision maker is to minimize the distance travelled by overloaded trucks by placing WIM stations in appropriate locations. They use a parameter to represent the maximum distance an overloaded truck is willing to travel in addition to its original route to avoid enforcement (tolerance) and attempt to create a situation where no routes are available within this tolerance. The authors simplify the original bilevel model into a single level model, called the Evasive Flow Capture Problem (EFCP), which allows for exact solutions to be found using appropriate algorithms, guaranteeing optimality of the solution found. The authors also provide a stochastic formulation for the same problem.

The original EFCP formulation has a limitation where a required optimization parameter is knowing all k possible paths for each origin-destination pair within the maximum tolerance parameter. However, these paths can be computationally expensive to obtain and, therefore, not always available, especially for complex road networks. Several papers have proposed alternative approaches to solve the EFCP, which aim to reduce the computational cost but may compromise the optimality of the final solution. Arslan, Jabali, and Laborte (2018) present a model and algorithm that can solve the EFCP without requiring knowledge of all possible paths in advance, while also keeping the optimality of the final solution. They use a custom branch and cut algorithm to dynamically find paths during the solution process, enabling the EFCP to be applied to complex road networks with fewer computational resources.

Therefore, the formulations proposed by Marković, Ryzhov, and Schonfeld (2015) and the solution strategy proposed by Arslan, Jabali and Laborte (2018) are considered optimal approaches for solving the mathematical problem of WIM placement to minimize enforcement evasion. These models enable an effective distribution of WIM stations over a network to ensure that the main traffic flows are forced to pass through a WIM station at least once during their trips. However, implementing these models for WIM network planning requires considerable effort, and may not be a trivial task. Despite this, the gains in enforcement efficiency by choosing smart placements for WIM stations justify the investment of resources.

3. Case Study

We conducted a case study using data from the state of Espírito Santo, Brazil to demonstrate the application of the Arslan, Jabali, and Laborte (2018) model for determining optimal WIM station placement. To reflect a practical scenario, we added a new constraint to limit the number of WIM stations to at most four, which is represented as a sum of all binary decision variables. The maximum deviation parameter was set at 20%, assuming that overloaded vehicles would travel up to 20% more than their original distance to evade enforcement. The state's long-distance road network was then represented using the required model parameters. The four optimal locations determined by the optimization model for WIM placement are shown in Figure 1.

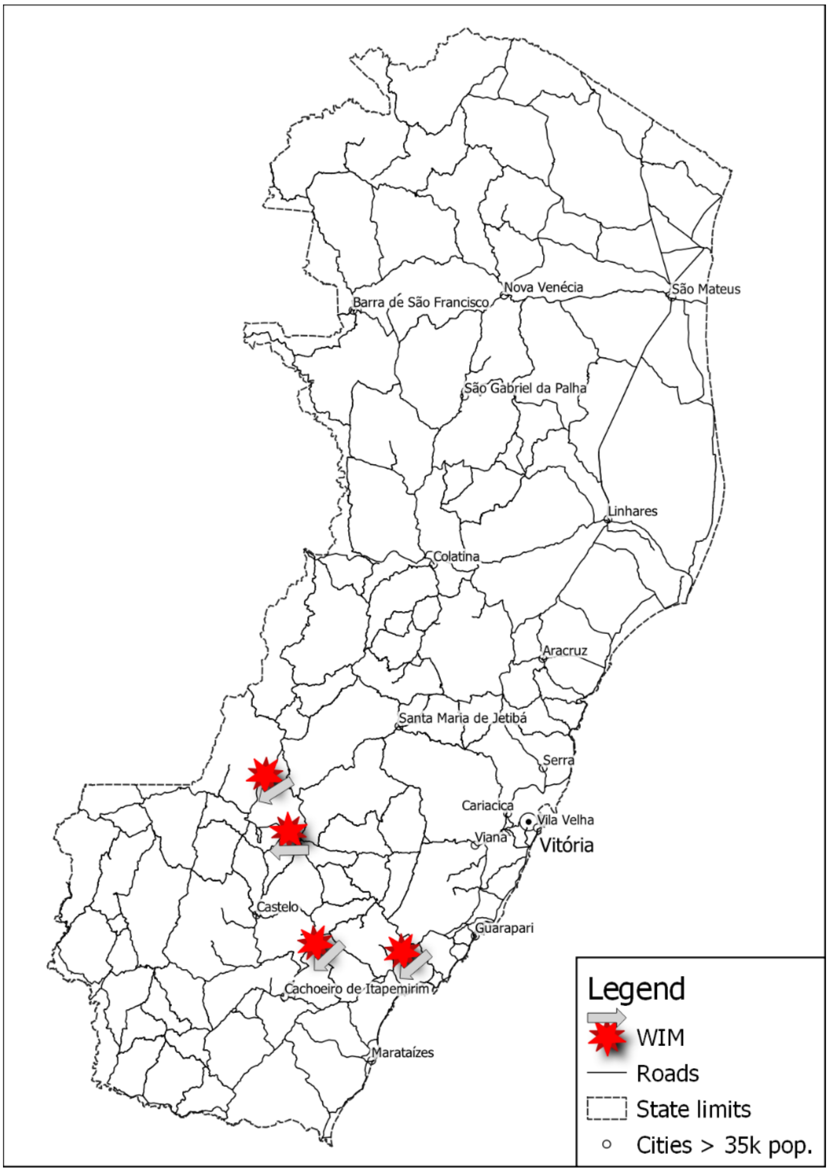

Figure 1 – Optimal placement of four WIM stations on the case study, obtained by the implemented model.

The presented solution displayed a significant concentration of WIM stations in a particular area of the network. We interpret this to be related to the fact that the EFCP formulation assumes that a WIM station has a positive impact only when there are no possible routes for evasion around it. If there are any such routes, the influence of the WIM station is considered negative. Therefore, the model needs to position the WIM stations near each other to achieve positive outcomes, ensuring that no escape routes remain open for the primary freight flows. However, not all overloaded carriers in reality will attempt to evade enforcement, and WIM stations can have a positive impact even if evasive routes are feasible. In practical situations, it may be preferable to distribute the WIM stations across other regions of the network while still looking for placements that minimize the existence of evasive routes. To approach this, one could work with the stochastic formulations provided by Marković, Ryzhov, and Schonfeld (2015) instead of the deterministic ones.

The results also reveal that the model aims to create a barrier of WIM stations around the major origins and destinations of traffic. Specifically, in this case study, the city of Vitória, which contains a port that receives high cargo volumes, was identified as a crucial flow hub, with a significant amount of traffic leaving the state to the southwest region where some of Brazil's largest cities are located. The model was successful in recognizing this pattern and recommended the placement of WIM stations to ensure that these flows could not bypass the monitoring process. This conclusion is also due to the type of data used for the simulation, which was volume flow data encompassing all states in Brazil and their respective freight movements. If the available data was focused on the internal transport lines, the proposed solution would then be focused on monitoring those routes.

In this case study, a metric called "damage reduction" was observed. This metric measures the damage caused by overloaded vehicles as a product of flow volumes and distance travelled. The damage is considered to be zero for monitored flows, where there are no viable unmonitored routes within the 20% distance tolerance (which is also true for the model). Initially, the metric is obtained for the unmonitored case, and then for the case where the four proposed WIM stations are installed. The results of the case study showed a reduction of 89.2%, indicating that the WIM systems successfully surrounded the most important flows and that the flows in other regions or in the opposite direction of the WIM barrier only represented a small percentage of the possible damage caused by overloading.

4. WIM Deployment Strategy

Although WIM location optimization models are a valuable tool to determine WIM placement and minimize evasion, relying solely on these models to plan a WIM network distribution is not advisable. These models have a limitation in that they focus only on enforcement evasion and overlook other critical factors such as infrastructure availability, possible variations in the actual, local overloading situation, political limitations, hazardous material transport routes, traffic safety data, amongst many other relevant information. Additionally, the models may prioritize optimal placement near important transport flows, neglecting other areas of the network. However, failing to consider these factors can also compromise network effectiveness by leaving open routes for carriers to continue traveling overweight. Therefore, optimization models should be used as part of the decision-making process for WIM deployment planning, providing placement alternatives for further consideration.

To address this, we propose the “WIM deployment strategy”: a series of steps that may be performed to plan and deploy WIM systems on a given road network. The proposal is based on a review of WIM placement methods published around the world and builds on the experience of road infrastructure operators and transport agencies in different countries with the implementation of WIM networks. The proposed strategy has five main phases: Initiation, Planning, Confirmation, Deployment and Evaluation.

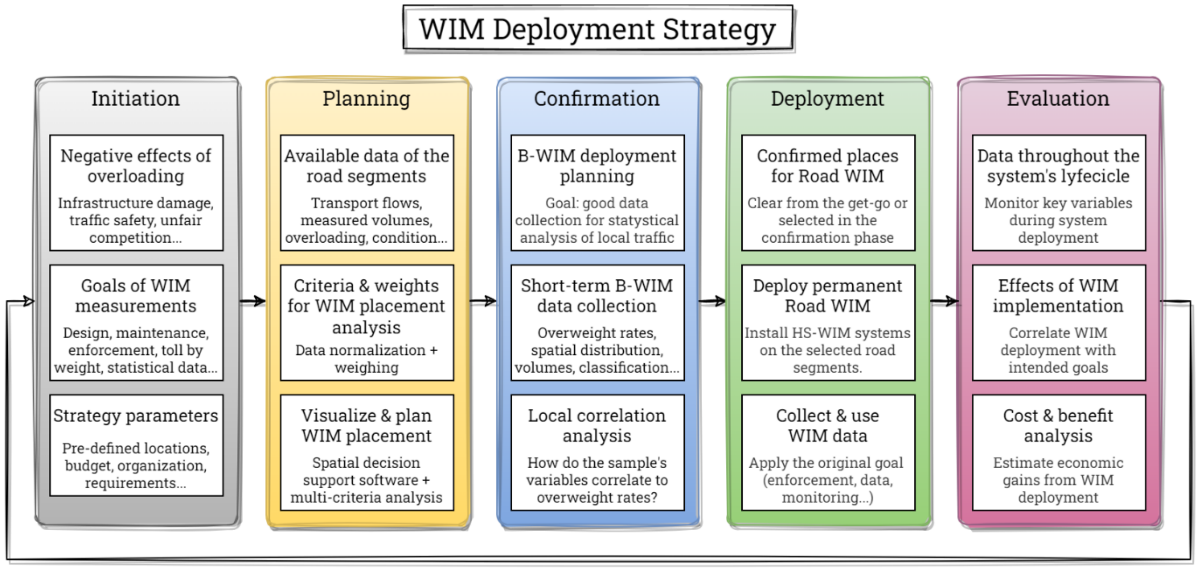

Figure 2 – WIM deployment strategy.

In the Initiation phase, the context of the WIM deployment must be described as much as possible: what are the current negative effects of the overloading in the local context, what are the goals of the application of the WIM network and its parameters (available budget, number of stations, etc.). Following the initiation, the second Planning phase starts with gathering all available and relevant data of the road network and transport flows in the study region. This information is used together with optimization models and other decision support tools, such as spatial visualization software (Franceschi *et al*., 2022), to place the WIM points that will initially compose the network.

The next Confirmation phase consists in planning and executing a short-term study, in which B-WIM systems (that are portable and moveable) are installed on a selected set of bridges within the study region, in a way that the locations and timeframe chosen are representative of the region's roads and traffic. The systems are activated, and data is collected for a limited period (e.g., 2 – 4 weeks). A statistical analysis is then performed on the collected data, so that the correlation between the local variables (road access level, location, economy, traffic classification, etc.) and the actual overloading situation is known. The latter consists of the absolute and relative overloading in gross vehicle weights, axle groups and single axle loads and the distribution of overloading over direction, different vehicle classes, time of day, day of the week, The end-goal of the confirmation phase is to understand where the most critical overweight is located and where the future permanent Road-WIM systems will be most effective.

At the start of the Deployment phase a set of confirmed placements for permanent Road-WIM installations is then known, composed by locations that are either clearly known from the start of the project or confirmed as a critical location during the confirmation phase. Now, the permanent HS-WIM systems may be installed in those locations, and their data collected and applied for the originally intended goal. Data must also be collected and stored for the Evaluation phase, where the results of the WIM deployment are quantified. Here, studies are done to measure results such as the impact of the WIM network on the overweight rates, heavy vehicle crash numbers, or maintenance costs, for example. Cost & benefit analyses may be performed to understand how well the WIM network has achieved its intended goal.

The proposed strategy for WIM network deployment is designed to provide a useful starting point for road entities worldwide, who are embarking on the process of planning and implementing WIM networks for enforcement or other purposes. The strategy takes into consideration various aspects to create a well-rounded approach. It recognizes that while WIM location optimization models are an important tool for finding the optimal WIM points, relying solely on these models can lead to a narrow focus on enforcement evasion, and neglect other critical factors. The WIM implementation strategy has been accepted and partially implemented in the Republic of Serbia by the Public Enterprise Road of Serbia and in the Republic of Georgia by the Roads Department of Georgia (van Loo *et al.*, 2022).

As such, the proposed strategy emphasizes the importance of taking a holistic approach when planning WIM networks and encourages decision-makers to consider all relevant factors to create a comprehensive deployment plan. While we believe the strategy represents a significant step forward in this process, it must be tested in a real-world scenario to ensure its effectiveness and make any necessary adjustments. Only through such testing and adjustments can the strategy be refined and improved to meet the needs of road entities worldwide. Ultimately, the goal of this proposal is to help create more effective and efficient WIM networks that can improve road safety and compliance with weight regulations.

5. Conclusions

The implementation of Weigh-in-Motion (WIM) networks is a crucial step towards improving road safety, reducing road damage, and increasing compliance with weight regulations. By accurately detecting and recording the weight of vehicles in motion, WIM systems can identify and deter overweight vehicles, ultimately reducing the risk of accidents and damage to infrastructure.

Optimization models for WIM placement are essential tools that can aid in planning the deployment of WIM networks. These models consider network topology and traffic patterns to determine the optimal location for WIM stations to maximize the flow capture. However, while optimization models provide valuable alternatives, they should not be the only basis for deployment planning. It is crucial to consider other factors, such as political and economic limitations, as well as the practical aspects of installing and maintaining WIM systems.

To address these challenges, we propose the WIM deployment strategy, a comprehensive approach to planning and deploying WIM networks. This strategy consists of five phases: Initiation, Planning, Confirmation, Deployment, and Evaluation. The proposed strategy considers optimization models as a part of the process while also considering other important steps such as data collection and improvement of the models using real collected data.

In conclusion, we believe that the proposed WIM deployment strategy is a useful framework for planning and deploying WIM networks worldwide. By considering all relevant factors and taking advantage of mathematical optimization models, decision-makers can create a well-rounded approach that leads to more effective and efficient WIM networks. We recommend that the proposed strategy be tested and adjusted based on real-world scenarios to ensure its effectiveness and refine it further to meet the needs of road entities. Ultimately, the goal of this proposal is to improve road safety, reduce road damage, and increase compliance with weight regulations, making roads safer and sustainable.

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7. References

- Ammarapala, V., Chinda, T., Udomworarat, P., Rongwiriyapanich, T., Khampanit, A., Suanmali, S. and Samphanwattanachai, B. (2013) "Selection of weigh station locations in Thailand using the analytic hierarchy process," Songklanakarin Journal of Science and Technology, 2013.
- Arslan, O., Jabali, O., and Laporte, G. (2018). "Exact Solution of the Evasive Flow Capturing Problem". Operations Research, 66(6), 1625–1640.
- Bogyrbayeva, A., and Kwon, C. (2021). "Pessimistic evasive flow capturing problems". European Journal of Operational Research, 293(1), 133–148.
- Franceschi, L., Otto, G. G., Kaesemodel, L., and Valente, A. M. (2020). "Effects of drivers' evasive behavior on the placement of automated enforcement equipment in highway systems". TRANSPORTES, 28(5), 235–251. doi: 10.14295/transportes.v28i5.2233
- Franceschi, L., Otto, G. G., Sobrosa, C. Q., Tani, V. Z., and Valente, A. M. (2022). "Where to place WIM stations? The Brazilian Approach Including a Novel Data-Driven Spatial Decision Support System" in Proceedings of the 40th Annual Southern African Transport Conference 2022.
- Ghisolfi, V., Ribeiro, G. M., Chaves, G. L. D., Orrico Filho, R. F., Hoffmann, I. C. S., and Perim, L. R. (2019). "Evaluating Impacts of Overweight in Road Freight Transportation: A Case Study in Brazil with System Dynamics". Sustainability, 11, 3128. doi: 10.3390/su11113128
- Hooshmand, F., and Mirhassani, S. A. (2018). "An Effective Bilevel Programming Approach for the Evasive Flow Capturing Location Problem". Networks and Spatial Economics, 18(4), 909–935.
- Jinyu, J., Xu, Z., and Zhongzhen, Y. (2020). Locating Control Stations for Mobile Monitoring of Overloaded Trucks on Rural Highways. IEEE Access, 8, 65821–65829.
- Kulović, M., Injac, Z., Davidović, S., and Posavac, I. (2018). "Modelling Truck Weigh Stations' Locations based on Truck Traffic Flow and Overweight Violation: A Case Study in Bosnia and Herzegovina". PROMET - Traffic&Transportation, 30(2), 163–171.
- Lu, C.-C., Yan, S., Ko, H.-C., and Chen, H.-J. (2018). "A Bilevel Model with a Solution Algorithm for Locating Weigh-In-Motion Stations". IEEE Transactions on Intelligent Transportation Systems, 19(2), 380-389.
- Mahmoudabadi, A. and Seyedhosseini, S.M. (2013). "Improving the efficiency of weigh in motion systems through optimized allocating truck checking oriented procedure". IATSS Research, 36(2), 123-128.

- Marković, N., Ryzhov, I.O. and Schonfeld, P. (2015). "Evasive flow capture: Optimal location of weigh-in-motion systems, tollbooths, and security checkpoints". Networks, 65(1), 22-42.
- Marković, N., Ryzhov, I.O. and Schonfeld, P. (2017). "Evasive flow capture: A multi-period stochastic facility location problem with independent demand". European Journal of Operational Research, 257(2), 687-703.
- Rygula, A., Brzozowski, K. and Maczyński, A. (2020). "Limitations of the effectiveness of Weigh in Motion systems". Open Engineering, 10(1), pp.183-196.
- Sayyady, F., Fathi, Y., List, G. F., and Stone, J. R. (2013). "Locating Traffic Sensors on a Highway Network". Transportation Research Record: Journal of the Transportation Research Board, 2339(1), 30–38.
- Van Loo, H., Branković, R., Radović, N., Tsibadze, G., Japardize, G. (2022). “A Hybrid WIM Implementation Strategy” in Proceedings of the 40th Annual Southern African Transport Conference, 2022, Pretoria, South Africa.