

## FROM TECHNICAL SPECIFICATIONS TO OPERATIONAL ALIGNMENT: FIREFIGHTING VEHICLE PLANNING IN RURAL AREAS

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**Abstract.** Efficient fire response in rural areas depends not only on the availability of firefighting vehicles, but also on the alignment between their technical parameters and real operational conditions. In practice, vehicle selection is often based on generalized regulatory requirements, with limited consideration of terrain accessibility, water supply constraints, and infrastructure variability. This study evaluates the suitability of firefighting vehicle technical parameters for rural operational environments using a mixed-method approach. The research combines engineering calculations, technical analysis, and empirical data from the State Fire and Rescue Service of Latvia, including a comparative assessment of Scania P370 and Iveco FF150E32W firefighting vehicles. To ensure comparability between parameters, a normalized Operational Alignment Index (OAI) is introduced. The index integrates mobility, water supply capability, and ergonomic factors into a unified evaluation framework. The results demonstrate that operational effectiveness depends on the compatibility of technical parameters with operational conditions rather than on individual performance metrics. The findings support the application of data-driven approaches in firefighting vehicle planning. The calculated operational indicators demonstrate that autonomous firefighting duration may decrease to approximately 6.8 minutes under high-intensity deployment conditions, emphasizing the importance of operational compatibility in rural environments.

**Keywords:** firefighting vehicles; rural areas; operational alignment; resource planning.

### Introduction

Firefighting operations in rural areas represent a specific operational context characterized by limited infrastructure, dispersed settlements, and restricted access to water supply systems, which constitutes a major operational challenge in rural firefighting [1]. In contrast to urban environments, where hydrant networks and transport accessibility are well developed, rural territories often require firefighting units to operate under conditions of uncertainty, including long response distances, variable terrain, and delayed reinforcement [2].

Previous studies on emergency response systems have primarily focused on response time optimisation, resource allocation, and station location modelling. Dynamic relocation algorithms and maximal covering models have been widely applied to improve emergency response efficiency [3; 4]. More recent approaches incorporate stochastic modelling, operational analytics, and emergency vehicle deployment optimisation to support decision-making under uncertainty [5-7]. However, most existing studies focus on urban emergency systems or generalized optimisation models and provide limited consideration of the operational compatibility between firefighting vehicle parameters and rural environmental conditions.

The effectiveness of firefighting operations depends not only on the availability of technical resources but also on their suitability for real operational conditions. Firefighting vehicles serve as primary response units responsible for water supply and initial fire suppression. In practice, vehicle procurement is often based on standardized technical specifications derived from regulatory requirements. While such an approach ensures compliance, it does not necessarily guarantee optimal performance in rural conditions. Earlier technical investigations have primarily focused on improving individual technical components. However, such approaches do not consider the interaction between parameters within real operational environments.

In rural firefighting environments, operational effectiveness depends not only on isolated technical parameters, but also on the interaction between vehicle mobility, water supply capability, terrain accessibility, and crew usability under real deployment conditions. Existing procurement approaches are typically based on standardized compliance criteria and nominal technical specifications, which may not adequately reflect operational realities in rural territories. As a result, firefighting vehicles with similar nominal characteristics may demonstrate substantially different operational performance in practice.

The novelty of this study lies in the development of an integrated Operational Alignment Index (OAI) that combines engineering calculations, operational indicators, and survey-based evaluations into

a unified decision-support framework for rural firefighting vehicle planning. Unlike conventional approaches focused on isolated technical characteristics, the proposed framework evaluates the compatibility between technical specifications and operational deployment conditions. This study introduces the concept of operational alignment, defined as the compatibility between technical parameters and operational conditions. Unlike traditional approaches, the study integrates engineering calculations, empirical data, and a formalized evaluation index into a unified framework.

## Materials and methods

The study applies a mixed-method approach combining engineering calculations, technical analysis, and empirical evaluation.

### *Data sources*

The analysis is based on:

- technical specifications of firefighting vehicles
  - Scania P370,
  - Iveco FF150E32W;
- operational calculation models;
- CTIF statistical data [2];
- survey data from 40 firefighting personnel.

Both vehicles have similar nominal parameters (3000 L water tank and 3000 L·min<sup>-1</sup> pump capacity), enabling comparative analysis beyond basic specifications.

### *Definition of variables*

Two groups of variables are considered:

- technical parameters
  - water tank capacity,
  - pump performance,
  - mobility characteristics,
  - engine power,
  - equipment configuration;
- operational indicators
  - autonomous operation time,
  - maneuverability,
  - stability,
  - ergonomics,
  - safety.

The selection of variables is based on their relevance to operational performance and their measurability within real firefighting scenarios.

### *Operational calculation model*

Operational performance is evaluated using deterministic engineering calculations based on flow rate, pressure, and resource constraints.

Autonomous operation time is calculated using Equation (1):

$$t = \frac{V}{Q}, \quad (1)$$

where  $t$  – autonomous operation time, min;  
 $V$  – water volume in the tank, L;  
 $Q$  – water flow rate, L·min<sup>-1</sup>.

This equation defines the duration of autonomous firefighting operations depending on the available water volume and consumption rate.

The relationship between flow rate and autonomous operation time is illustrated in Fig. 1.

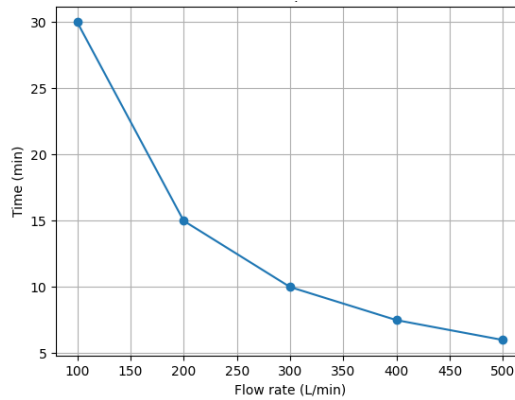


Fig. 1. Autonomous operation time depending on water consumption rate

Foam generation is calculated using Equation (2):

$$V_{foam} = V_{water} \times k \quad (2)$$

where  $V_{foam}$  – volume of foam solution, L;  
 $V_{water}$  – volume of water used, L;  
 $k$  – foam concentrate proportion coefficient.

This equation determines the available foam solution volume depending on water usage and foam concentrate proportion.

Hydraulic limitation is calculated using Equation (3):

$$l = \frac{H_p - H_l - Z}{S \times Q^2}, \quad (3)$$

where  $l$  – maximum operational distance, m;  
 $H_p$  – pump pressure, m;  
 $H_l$  – pressure losses in the hose line, m;  
 $Z$  – elevation difference, m;  
 $S$  – hydraulic resistance coefficient;  
 $Q$  – flow rate,  $L \cdot s^{-1}$ ;

This equation defines the maximum operational distance limited by hydraulic conditions of the water supply system. These calculations are consistent with established fire dynamics and water supply modelling approaches [8; 9].

Equations (1)-(3) describe water supply limitations, foam application, and operational range. The calculated operational indicators are used as input variables for the Operational Alignment Index, enabling integration of engineering results into a unified evaluation framework. Although originally developed for emergency medical services, similar optimisation approaches are applicable to firefighting systems, taking into account differences in incident characteristics and operational constraints [5].

#### Operational Alignment Index

An Operational Alignment Index (OAI) is introduced as a method to evaluate compatibility between technical parameters and operational conditions, based on multi-criteria decision analysis [10; 11].

Parameters are normalized using Equation (4):

$$x_i^* = \frac{x_i - x_i^{\min}}{x_i^{\max} - x_i^{\min}}, \quad (4)$$

where  $x_i^*$  – normalized value of parameter  $i$ ;  
 $x_i$  – original value of parameter  $i$ ;  
 $x_i^{\min}$  – minimum value of parameter  $i$ ;  
 $x_i^{\max}$  – maximum value of parameter  $i$ .

Min-max normalization is applied to ensure comparability between parameters with different units and scales, transforming them into a dimensionless range  $[0, 1]$ , as commonly used in data preprocessing and decision-support models.

The index is calculated using Equation (5):

$$OAI = \sum_{i=1}^n w_i x_i^* , \quad (5)$$

where  $OAI$  – Operational Alignment Index;  
 $w_i$  – weight coefficient of parameter  $i$ ;  
 $x_i^*$  – normalized value of parameter  $i$ .

This equation integrates multiple normalized parameters into a single index representing the level of operational alignment. Weights are calculated as normalized mean values of survey responses, ensuring that their sum equals 1, which corresponds to common approaches in multi-criteria decision analysis [12].

#### *Survey methodology*

A structured survey involving 40 firefighting personnel from the State Fire and Rescue Service of Latvia was conducted between January and March 2025. Respondents included vehicle operators, crew commanders, and operational personnel with practical experience in rural firefighting operations. The survey applied a 5-point Likert scale to evaluate maneuverability, stability, ergonomics, safety, and overall operational suitability of firefighting vehicles under rural deployment conditions. Survey responses were anonymized and processed using descriptive statistical analysis. Mean values were calculated for each evaluation criterion and subsequently normalized for integration into the Operational Alignment Index. Weight coefficients used in the OAI model were derived from normalized mean survey scores, ensuring proportional representation of operational priorities identified by firefighting personnel. For example, maneuverability received the highest normalized weight coefficient ( $w = 0.26$ ), followed by ergonomics ( $w = 0.22$ ) and operational stability ( $w = 0.21$ ).

#### *Limitations*

The study is limited by sample size and the use of linear aggregation in the index, which may oversimplify complex interdependencies between parameters. Interdependencies between parameters are not explicitly modelled.

## **Results and discussion**

Operational calculations show that firefighting vehicles with a 3000 L water tank provide limited autonomous operation time, especially under high-intensity conditions.

Table 1

**Key operational indicators**

| Parameter                   | Value | Units               |
|-----------------------------|-------|---------------------|
| Autonomous time (1 nozzle)  | ~13.5 | min                 |
| Autonomous time (2 nozzles) | ~6.8  | min                 |
| Pump capacity               | 3000  | L·min <sup>-1</sup> |
| Tank volume                 | 3000  | L                   |

The results indicate that operational effectiveness is constrained by resource availability and system limitations. The calculated autonomous operation time demonstrates a significant operational limitation for rural firefighting scenarios where external water supply may not be immediately available. Under high-intensity firefighting conditions involving two active nozzles, autonomous operation time decreases to approximately 6.8 minutes, which may be insufficient in remote areas characterized by extended response and reinforcement times. Similar limitations related to water supply sustainability in rural firefighting operations have been identified in NFPA rural firefighting standards and operational water supply studies [1; 9]. The results confirm that nominal tank capacity alone cannot ensure operational effectiveness without considering deployment context and resource accessibility.

Survey results show that Scania P370 achieves higher ratings in maneuverability, stability, ergonomics, and safety. These factors significantly influence real operational performance, as confirmed

in emergency response travel time studies [12]. The higher evaluation scores achieved by the Scania P370 indicate that operational performance is strongly influenced by factors beyond nominal pump capacity and water tank volume. Improved maneuverability and ergonomic characteristics contribute to more effective deployment under rural terrain conditions, particularly on narrow access roads and uneven surfaces. This observation is consistent with operational research emphasizing the importance of accessibility, deployment suitability, and response efficiency in emergency systems [3; 7; 12]. The findings suggest that vehicle procurement decisions should incorporate operational usability criteria alongside standardized technical specifications.

The comparative operational assessment results are summarized in Fig. 2.

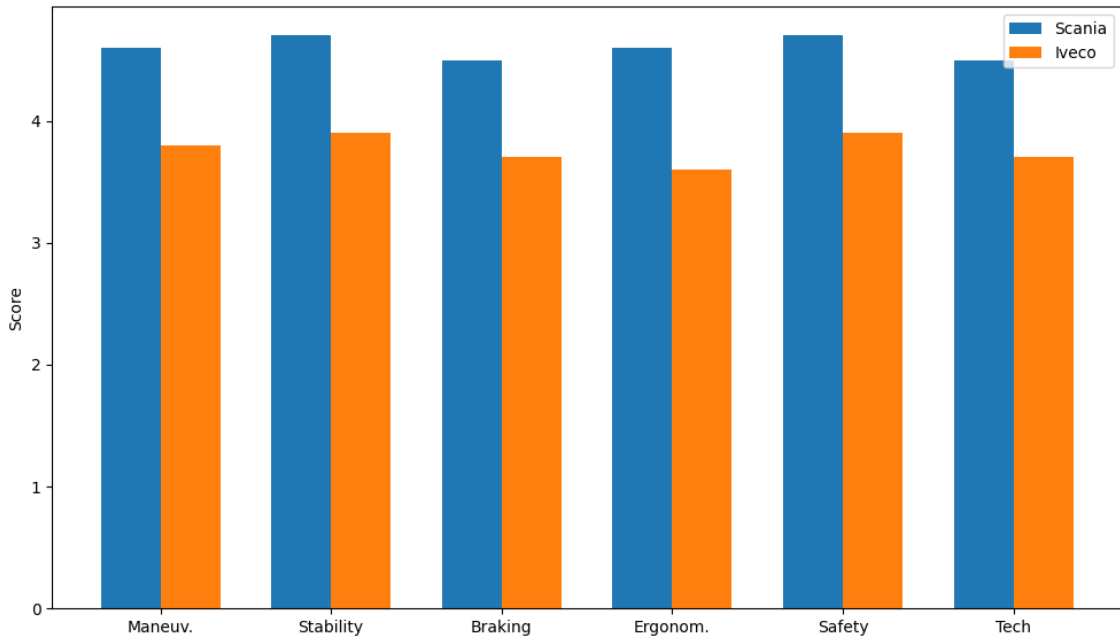


Fig. 2. Comparative evaluation of firefighting vehicle performance

The combined analysis demonstrates that performance is determined not by individual parameters, but by their interaction with operational conditions.

The conceptual relationship between operational alignment and firefighting effectiveness is illustrated in Fig. 3.

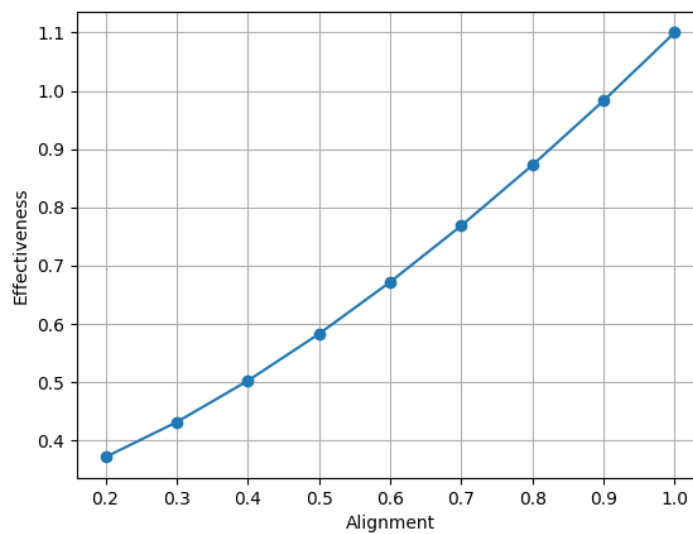


Fig. 3. Relationship between operational alignment and firefighting effectiveness

A consistent relationship between calculated indicators and survey-based evaluations can be observed.

The proposed Operational Alignment Index enables quantitative evaluation of this relationship. Higher index values correspond to improved operational effectiveness.

The calculated Operational Alignment Index across different scenarios is presented in Fig. 4.

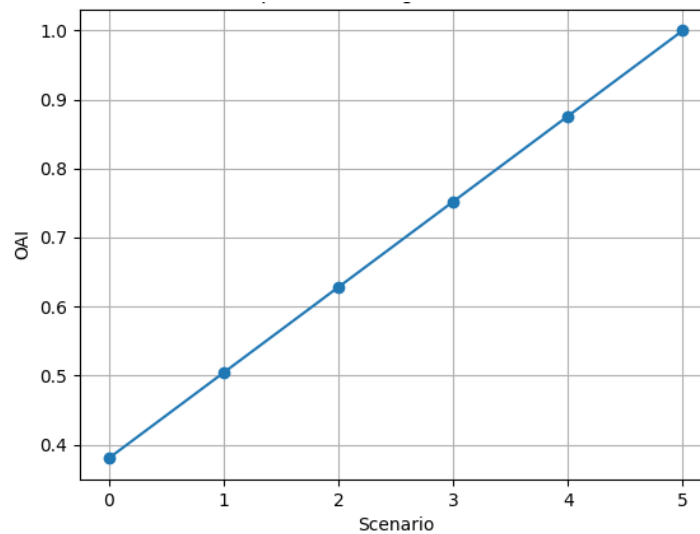


Fig. 4. Operational Alignment Index across different operational scenarios

The obtained OAI values demonstrate that operational suitability varies significantly despite comparable nominal technical specifications, confirming the importance of context-oriented vehicle evaluation in rural firefighting systems. The proposed index is intended as a comparative decision-support tool rather than an absolute predictive measure of operational effectiveness. Although the proposed Operational Alignment Index provides a structured evaluation framework, several limitations should be acknowledged. The study is based on a limited sample of operational personnel and two vehicle configurations, which restricts the generalizability of the findings. Furthermore, the linear aggregation approach applied in the OAI model may not fully capture nonlinear interactions between operational variables. The study should therefore be interpreted as an exploratory evaluation approach intended to support comparative operational assessment rather than direct operational prediction. Nevertheless, the consistent relationship observed between engineering calculations and survey-based evaluations indicates that the proposed framework can support evidence-based firefighting vehicle planning in rural territories. The findings suggest that standardized procurement approaches should be complemented by context-specific evaluation.

## Conclusions

1. The performed operational calculations demonstrate that firefighting vehicles equipped with a 3000 L water tank provide limited autonomous firefighting capacity in rural conditions, with operational duration decreasing from approximately 13.5 minutes under single-nozzle operation to 6.8 minutes when two nozzles are simultaneously deployed.
2. Survey-based evaluation involving 40 firefighting personnel confirmed that maneuverability, ergonomics, and operational stability significantly influence real deployment effectiveness under rural conditions. The Scania P370 achieved consistently higher operational evaluation scores compared to the Iveco FF150E32W despite similar nominal technical specifications.
3. The results demonstrate that operational effectiveness depends on the compatibility between technical parameters and deployment conditions rather than on isolated technical characteristics alone. Standardized procurement approaches based exclusively on nominal specifications may therefore be insufficient for rural firefighting environments.
4. The proposed Operational Alignment Index integrates engineering calculations, operational indicators, and empirical survey evaluations into a unified decision-support framework. The model enables quantitative assessment of operational suitability across different deployment scenarios.
5. The study contributes to the development of data-driven firefighting resource planning approaches for rural territories. Future research should incorporate GIS-based modelling, nonlinear parameter

interactions, and larger-scale operational datasets to improve model applicability and predictive capability.

### Author contributions

Conceptualization, V.P.; methodology, V.P. and A.S.; validation, J.P. and T.T.; formal analysis, V.P. and A.S.; investigation, V.P., A.S., J.P. and T.T.; writing-original draft preparation, V.P.; writing-review and editing, J.P. and T.T.; project administration, V.P. All authors have read and agreed to the published version of the manuscript.

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