Significance of terrain-based haptic feedback for motion platform accuracy in firefighting vehicle simulation

Znaczenie haptycznego sprzężenia zwrotnego opartego na profilu terenu dla dokładności platformy ruchu w symulatorze pojazdu strażackiego

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This study explores the integration of terrain-based haptic feedback in a fire truck driving simulator to improve training realism and efficiency. A wide range of terrain conditions–including slopes, mud, and uneven surfaces–was simulated and dynamically mapped to a 6DOF motion platform. The system reproduces realistic vehicle dynamics and terrain-induced forces, enhancing driver immersion and decision-making in extreme conditions. Compared to previous research, the simulator offers greater fidelity and scenario diversity, supporting faster skill acquisition and better operational readiness for real-world emergencies.

KEYWORDS: driving simulator, fire truck simulator, haptic feedback, simulators

W artykule przedstawiono podejście do zwiększenia realizmu i skuteczności szkoleń kierowców pojazdów straży pożarnej poprzez zastosowanie haptyki opartej na profilu terenu. Symulacje obejmowały różnorodne warunki terenowe, takie jak strome podjazdy, błoto czy wyboje, które odwzorowywane były na platformie ruchomej o sześciu stopniach swobody. System umożliwia realistyczne odwzorowanie dynamiki pojazdu oraz sił wynikających z ukształtowania terenu, co poprawia immersję i wspiera podejmowanie decyzji w warunkach ekstremalnych.

SŁOWA KLUCZOWE: symulator jazdy, symulator pojazdu strażackiego, sprzężenie zwrotne haptyczne, symulatory.

Introduction

Training with modern simulators offers numerous benefits, including improved participant skills, enhanced safety during the training process, and reduced learning time. This approach can significantly lower training costs by eliminating expenses related to fuel, maintenance, or potential repairs–even under extreme or unusual conditions. It also has a positive environmental impact by eliminating exhaust emissions. The level of training realism depends on various factors, such as vehicle interior fidelity, advanced 4K projection systems, spatial audio implementation, and precision in 3D world visualization. This is particularly crucial in railway, automotive, and combat simulators, which rely on realistic scenarios and detailed terrain models, enabling training in otherwise inaccessible or dangerous conditions. Firefighter training in simulated environments is especially valuable, offering realistic preparation for emergencies in a safe, controlled setting. When it comes to operating fire trucks, simulators can address both emergency response and road safety training. They allow navigation in varied weather conditions, reinforcing skills without risking health or life. Repeated scenario execution and training progress monitoring further support skill development and program optimization. Driving simulators are thus an effective tool for enhancing firefighter readiness across a wide range of operational contexts.

Among the critical elements influencing training effectiveness in driving simulators is the implementation of haptic feedback. Human haptic perception involves both kinesthetic (force-related) and tactile feedback, which together provide essential information during physical interactions like handling objects or locomotion [5]. Haptic systems provide users with tactile and force sensations that replicate real-world vehicle dynamics, such as steering resistance, road surface texture, or vehicle vibration. This sensory input enhances immersion and enables more accurate motor responses, closely resembling those required during actual vehicle operation. In emergency services training, particularly for fire truck driving, realistic force feedback is essential for developing precise handling skills, situational awareness, and appropriate reactions under stress. Without haptic cues, users may develop incorrect habits or misjudge vehicle behavior, reducing the transferability of simulator-based skills to real-world contexts. Therefore, integrating high-fidelity haptic feedback is fundamental for ensuring training realism, safety, and overall simulator effectiveness.

However, it is worth critically examining whether current haptic models are sufficiently flexible to accommodate the diversity of terrain scenarios encountered by firefighting vehicles. As highlighted in several studies [8], [3], many existing simulation systems are optimized for standard road conditions, with limited capability to reproduce complex off-road environments such as steep gradients, variable terrain surfaces, or serpentine roads. This limitation can hinder the transfer of skills to real-world emergency scenarios, particularly when operating heavy vehicles in challenging environments. Moreover, while the importance of haptic feedback in driving simulators is well documented [4], [2], [6], the degree to which terrain-

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based force cues affect driver performance–especially in high-risk, off-road emergency response–is still underexplored. For example, simulations focusing on handwheel torque feedback [4] or self-motion sensation through motion platforms [2] highlight improvements in realism, but often do not fully incorporate dynamically changing terrain conditions. As discussed in [1] and [7], multimodal feedback systems and firefighter-specific training environments show potential, yet often lack the physical terrain variability needed to replicate real-world dynamics, such as axle articulation, traction loss, or slope-induced body roll.

This paper therefore focuses on the significance of terrain-based haptic feedback in the context of vehicle dynamics and motion platform behavior in a firefighting vehicle simulator. Particular emphasis is placed on the integration of elevation and surface irregularities into motion cues, enabling more realistic and effective training for emergency vehicle operators. Unlike previous studies, which often addressed generic or simplified driving conditions, this work incorporates a wide range of terrain scenarios–including steep slopes, serpentine roads, uneven surfaces, and soft ground–allowing for more comprehensive evaluation of haptic responses and driver adaptation under diverse operational conditions.

Vehicle dynamics and motion platform integration

The vehicle physics model was developed in the Unity environment using Vehicle Physics Pro, an advanced simulation toolkit that allows for extensive customization of vehicle parameters and behavior. This flexible framework enabled the precise definition of firefighting vehicle dynamics, including several unique structural and operational characteristics. Key aspects of the model include accurate representation of dynamic properties specific to fire trucks, such as non-standard steering configurations (e.g., front and rear axles), high center of gravity, and variable mass distribution depending on the tank's fill level and the type of firefighting agent used.

For each vehicle configuration, a dedicated set of physical parameters was defined, including:

- Center of Mass (CoM): determined based on the distribution of operational loads and equipment,
- Inertia Tensor: reflects the mass distribution along the vehicle, directly influencing understeer/oversteer characteristics,
- Axle Definitions: associated with wheel positions, steering assignments, and braking functionality,
- Steering System: includes steering angles, wheel toe settings, and steering input mapping,
- Braking System: covers braking force distribution and handbrake characteristics,
- Tires: tire model and friction parameters, essential for traction and terrain interaction,
- Drivetrain Configuration: specifies the drivetrain type (e.g., RWD, AWD), including differentials and torque split logic,
- Engine: torque and power curves, rev limiter setup,

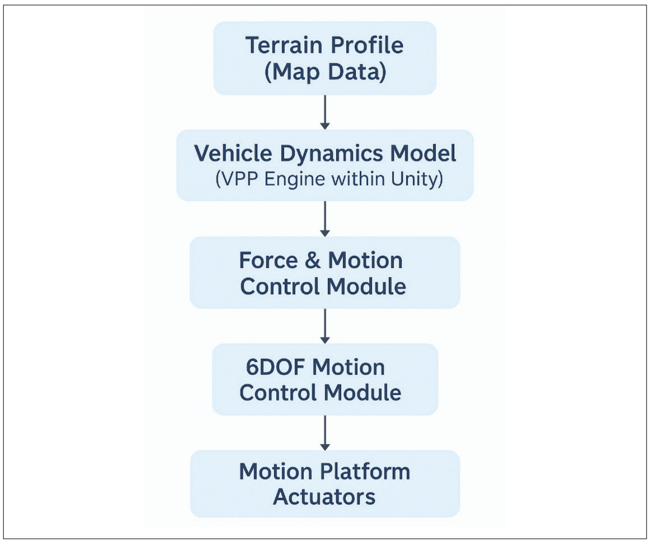

Fig. 1. Data Flow for Terrain-Based Haptic Integration in Firefighting Vehicle Simulator
Rys. 1. Przepływ danych dla integracji haptyki opartej na terenie w symulatorze pojazdu strażackiego

- Clutch: type and parameters, including torque converter behavior.
- Transmission: gearbox type and parameters:
  - automatic transmission
  - automatic with manual override (Tiptronic/ /M-mode)
  - manual transmission
  - manual with automated gear selection
- Retarder and auxiliary braking systems for heavy-duty vehicle deceleration.

In addition to the above, the dynamics model incorporates rolling resistance, aerodynamic drag, and tire grip coefficients. These parameters are used to compute the resultant forces acting on the vehicle, which are then translated into motion cues for the motion platform.

The overall data flow, from terrain input to motion platform actuation, is illustrated in Figure 1. The simulation software is driven by a vehicle motion equation solver integrated with a six-degree-of-freedom (6DOF) motion control module. This module enables full control over translational movements (X, Y, Z axes) and rotational displacements (roll, pitch, yaw), allowing the simulator to reproduce complex vehicle behaviors such as tilting, turning, and vertical displacement with high fidelity. The physical setup of the training system, including the vehicle simulator mounted on a 6DOF motion platform, is shown in Figure 2. The 6DOF Motion Control Module developed as part of this research supports realistic and synchronized motion responses, which are essential for accurately replicating driving dynamics in diverse terrain and operational scenarios. The platform's precise control is particularly important for simulating critical maneuvers, such as rapid lane changes, braking on gradients, or navigating uneven surfaces with varying elevation profiles. By leveraging motion equations and advanced control algorithms, the system can simulate a wide range of vehicles with diverse mass distributions, powertrain layouts, and mechanical, hydraulic, or pneumatic subsystems.

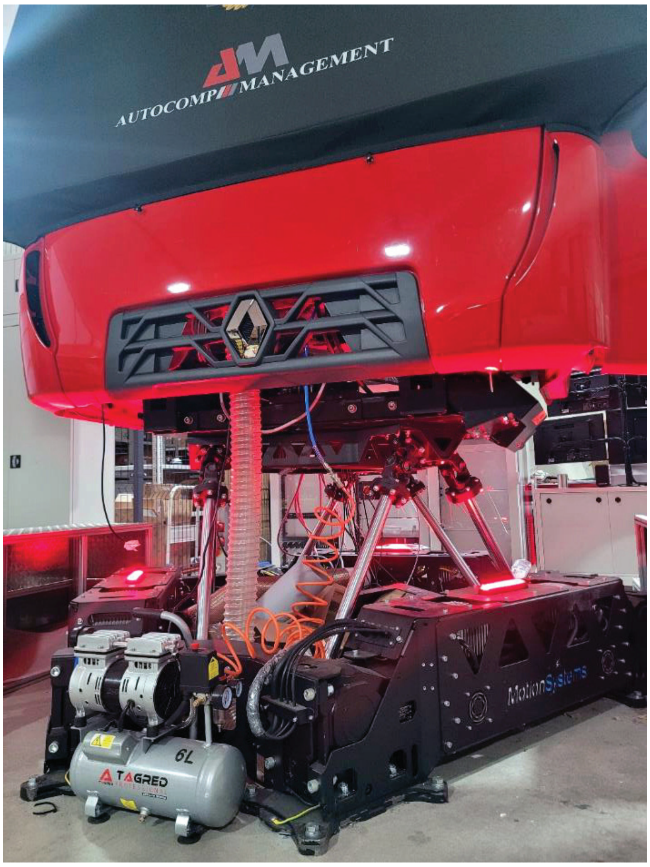

Fig. 2. Firefighting vehicle simulator mounted on a six-degree-of--freedom motion platform
Rys. 2. Symulator pojazdu strażackiego zamontowany na platformie ruchu o sześciu stopniach swobody

Implementation of terrain-based haptic feedback in motion platform control

To achieve realistic motion responses aligned with vehicle-terrain interactions, the simulation system incorporates terrain-based haptic feedback into the 6DOF motion platform control system. This coupling ensures that vehicle dynamics, particularly those influenced by terrain irregularities, are accurately transmitted to the operator through physical motion cues.

The haptic system interprets elevation changes–such as slopes, potholes, curbs, and surface roughness–as input signals that modify the platform's movement profile in real time. These elevation profiles are generated from high-resolution terrain maps and integrated into the physics engine as dynamic inputs affecting the vertical displacement (heave), roll, and pitch of the vehicle model.

To support comprehensive training scenarios, a wide range of terrain types has been implemented in the simulation environment, including:

- varied topography, such as flat terrain, hilly areas, and roads with varying gradients (e.g., long steep ascents/descents, undulating profiles, and serpentine roads),
- urban environments, featuring paved roads with intersections, roundabouts, traffic signals, and both low-rise and multi-story buildings,
- rural areas, characterized by paved roads and a mix of single- and two-story residential structures,
- unbuilt/open terrain, including dirt roads, single and dual carriageways, highways with multiple lanes per direction and crash barriers, and expressways with multi-level interchanges crossing over land and water transport routes,
- bridges, overpasses, and tunnels, which introduce elevation transitions and enclosure effects critical to motion cueing and situational awareness.

A core element of this process is the real-time mapping of terrain-induced forces onto the motion control algorithms. These include:

- vertical impulses caused by terrain height variations,
- lateral tilting and body roll during uneven cornering,
- pitch behavior from slope transitions,
- vibration profiles for various surface textures.

To maintain synchronization between visual stimuli and physical motion, a signal filtering and scaling system is employed. It ensures only relevant and perceptible haptic cues are passed to the platform, preventing unnatural movements. Low-pass filters reduce noise, while gain adjustments adapt intensity based on terrain and vehicle type.

Fig. 3. Off-road driving – muddy terrain – bogging simulation – in 3D visualization
Rys. 3. Jazda w terenie – błotnisty teren – symulacja ugrzęźnięcia – wizualizacja 3D

Fig. 4. Off-road driving on a lateral slope – 3D visualization
Rys. 4. Jazda w terenie po nachylonym zboczu – wizualizacja 3D

Fig. 5. Off-road driving over uneven terrain (obstacles causing axle articulation) – 3D visualization
Rys. 5. Jazda w terenie po nierównym podłożu (nierówności powodujące tzw. wykrzyż osi pojazdu) – wizualizacja 3D.

Fig. 6. Firefighting vehicle simulator – In-Cabin Visual Projection Geometry Setup
Rys. 6. Symulator pojazdu strażackiego – konfiguracja geometrii projekcji wizualizacji wewnątrz kabiny symulatora

The result is a deeply immersive simulation where realistic terrain input enhances motion fidelity and improves operator readiness in highly dynamic and varied driving conditions. Representative simulations of off-road driving scenarios are illustrated in figures 3, 4, and 5, including muddy terrain with bogging effects (fig. 3), driving on a lateral slope (fig. 4), and uneven terrain inducing axle articulation (fig. 5), all shown in 3D visualization.

In turn, fig. 6 illustrates the in-cabin visual projection geometry of the firefighting vehicle simulator, showing the visual layout as perceived by the trainee during simulation.

Conclusions

This paper addressed the challenge of enhancing the realism and effectiveness of firefighter vehicle driver training through the integration of haptic feedback and advanced terrain generation techniques. The developed simulations incorporated diverse terrain scenarios, including steep inclines, uneven surfaces, serpentine roads, and low-traction environments, with haptic cues precisely mapped to vehicle dynamics.

The integration of terrain-based haptic feedback significantly improves the efficiency of skill acquisition, enabling trainees to develop proper driving techniques in extreme off-road conditions more quickly and intuitively. This, in turn, translates into higher preparedness for emergency response operations.

Haptic realism–particularly the accurate reproduction of traction differences and terrain-induced forces–was shown to be essential for immersiveness and operational training quality. Combined with realistic 3D terrain modeling, it provides a training environment that closely mirrors real-world rescue conditions. Notably, this system goes beyond prior work by implementing a broader set of terrain configurations and more comprehensive physical interactions, which are often absent or simplified in earlier simulation studies.

Furthermore, haptic perception plays a crucial role in shaping users' decision-making abilities under pressure. Precise simulation of terrain variations and vehicle accelerations enables firefighters to better anticipate and respond to dynamic challenges, ultimately improving safety, precision, and effectiveness in real-life rescue missions. The findings support the conclusion that integrating high-fidelity haptics with terrain-aware vehicle simulation is a key factor in developing advanced, transferable training for emergency services.

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