ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN RISK MANAGEMENT IN THE ROAD TRANSPORT OF HAZARDOUS PRODUCTS IN BRAZIL: FUNDAMENTALS, APPLICATION, AND COMPLIANCE

INTELIGÊNCIA ARTIFICIAL E MACHINE LEARNING NA GESTÃO DO RISCO NO TRANSPORTE RODOVIÁRIO DE PRODUTOS PERIGOSOS NO BRASIL: FUNDAMENTOS, APLICAÇÃO E CONFORMIDADE

INTELIGENCIA ARTIFICIAL Y APRENDIZAJE AUTOMÁTICO EN LA GESTIÓN DE RIESGOS EN EL TRANSPORTE DE PRODUCTOS PELIGROSOS POR CARRETERA EN BRASIL: FUNDAMENTOS, APLICACIÓN Y CUMPLIMIENTO

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ABSTRACT

This article presents a complete and operational framework for applying Artificial Intelligence and Machine Learning to risk management in the road transport of hazardous materials in Brazil, focusing on reducing low-frequency, high-consequence losses, maintaining the level of logistical service, and ensuring regulatory compliance. The work aligns with Decree No. 96,044 of May 18, 1988, which approves the Regulations for the Road Transport of Hazardous Products, as well as the standards of the Brazilian Association of Technical Standards ABNT NBR 7500, concerning identification for the land transport of hazardous materials, and ABNT NBR 9735, which deals with the set of equipment for emergencies in the land transport of hazardous materials. Furthermore, state Technical Instructions are considered, with emphasis on Technical Instruction 32 of 2025 from the Fire Department of the Military Police of the State of São Paulo, which establishes parameters for prevention and response in buildings and risk areas involving hazardous materials. This article seeks to combine technical evidence from multimodal predictive models – such as Gated Recurrent Unit-type recurrent networks integrated with deep neural networks with multimodal incorporation – with risk-oriented route optimization methods, including the use of Conditional Value-at-Risk and the concept of risk equity among affected communities. The approach is complemented by telemetry and the "Internet of Things" with sensors certified for explosive atmospheres, and by international guidelines for electronic documentation in emergencies established within the framework of the United Nations Economic Committee for Europe. As an applied demonstration, the BR-116 corridor, known as Régis Bittencourt, for Class Three flammable liquid cargo – Flammable Liquids – is presented, with indicative results of a reduction in expected risk between twenty and thirty percent and a reduction in Conditional Value-at-Risk to ninety-five percent between thirty-five and forty percent, while preserving the delivery window and regulatory compliance.

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RESUMO

Este artigo apresenta uma estrutura completa e operacional para aplicação de Inteligência Artificial e Machine Learning na gestão do risco no transporte rodoviário de produtos perigosos no Brasil, com foco na redução de perdas de baixa frequência e alta consequência, manutenção do nível de serviço logístico e aderência normativa. O trabalho está alinhado ao Decreto nº 96.044 de 18 de maio de 1988, que aprova o Regulamento para o Transporte Rodoviário de Produtos Perigosos, bem como às normas da Associação Brasileira de Normas Técnicas ABNT NBR 7500, referente à identificação para o transporte terrestre de produtos perigosos, e ABNT NBR 9735, que dispõe sobre o conjunto de equipamentos para emergências no transporte terrestre de produtos perigosos. Além disso, são consideradas as Instruções Técnicas estaduais, com ênfase na Instrução Técnica 32 de 2025 do Corpo de Bombeiros da Polícia Militar do Estado de São Paulo, que estabelece parâmetros para prevenção e resposta em edificações e áreas de risco envolvendo produtos perigosos. Este artigo busca combinar evidências técnicas de modelos preditivos multimodais – como redes recorrentes do tipo Gated Recurrent Unit integradas a redes neurais profundas com incorporação multimodal – com métodos de otimização de rotas orientadas a risco, incluindo o uso do Valor Condicional em Risco, conhecido internacionalmente como Conditional Value-at-Risk, e o conceito de equidade de risco entre comunidades afetadas. A abordagem é complementada por telemetria e "Internet das Coisas" com sensores certificados para atmosferas explosivas, e por diretrizes internacionais de documentação eletrônica em emergências estabelecidas no âmbito do Comitê Econômico das Nações Unidas para a Europa. Como demonstração aplicada, apresenta-se o corredor BR-116, conhecido como Régis Bittencourt, para cargas de líquidos inflamáveis da Classe Três – Líquidos Inflamáveis, com resultados indicativos de redução do risco esperado entre vinte e trinta por cento e redução do Valor Condicional em Risco a noventa e cinco por cento entre trinta e cinco e quarenta por cento, preservando a janela de entrega e a conformidade normativa.

Palavras-chave: Inteligência Artificial. Aprendizado de Máquina. Produtos Perigosos. Gestão de Risco. Transporte Rodoviário. Telemática. IoT. CVaR. Equidade de Risco.

RESUMEN

Este artículo presenta un marco completo y operativo para aplicar la Inteligencia Artificial y el Aprendizaje Automático a la gestión de riesgos en el transporte terrestre de materiales peligrosos en Brasil, con foco en la reducción de pérdidas de baja frecuencia y alta consecuencia, el mantenimiento del nivel de servicio logístico y el cumplimiento normativo. El trabajo se alinea con el Decreto No. 96.044 del 18 de mayo de 1988, que aprueba el Reglamento para el Transporte por Carretera de Productos Peligrosos, así como con las normas de la Asociación Brasileña de Normas Técnicas ABNT NBR 7500, relativa a la identificación para el transporte terrestre de materiales peligrosos, y ABNT NBR 9735, que trata del conjunto de equipos para emergencias en el transporte terrestre de materiales peligrosos. Además, se consideran las Instrucciones Técnicas estatales, con énfasis en la Instrucción Técnica 32 de 2025 del Departamento de Bomberos de la Policía Militar del Estado de São Paulo, que establece parámetros para la prevención y respuesta en edificios y áreas de riesgo que involucran materiales peligrosos. Este artículo busca combinar la evidencia técnica de modelos predictivos multimodales —como redes recurrentes de tipo Gated Recurrent Unit integradas con redes neuronales profundas con incorporación multimodal— con métodos de optimización de rutas orientados al riesgo, incluyendo el uso del Valor en Riesgo Condicional y el concepto de equidad de riesgo entre las comunidades afectadas. El enfoque se complementa con telemetría e Internet de las Cosas (IoT) con

sensores certificados para atmósferas explosivas, así como con las directrices internacionales para la documentación electrónica en emergencias establecidas en el marco del Comité Económico de las Naciones Unidas para Europa. Como demostración aplicada, se presenta el corredor BR-116, conocido como Régis Bittencourt, para carga líquida inflamable de Clase Tres (Líquidos Inflamables), con resultados indicativos de una reducción del riesgo esperado de entre el 20 % y el 30 % y una reducción del Valor en Riesgo Condicional al 95 % entre el 35 % y el 40 %, preservando la ventana de entrega y el cumplimiento normativo.

Palabras clave: Inteligencia Artificial. Aprendizaje Automático. Productos Peligrosos. Gestión de Riesgos. Transporte por Carretera. Telemática. IoT. CVaR. Equidad de Riesgo.

1 INTRODUCTION

The transport of dangerous products by road in Brazil is an essential and sensitive activity, subject to a strict legal and technical regime. Decree No. 96,044 of 1988 establishes the fundamental rules for the road transport of dangerous products, while ABNT-NBR 7500 regulates identification and signaling and ABNT-NBR 9735 defines the minimum set of equipment for emergencies. At the state level, Technical Instructions, such as Technical Instruction 32 of 2025 of the São Paulo Fire Department, detail prevention and response requirements in buildings and risk areas. Such normative instruments, when integrated with data-based decision systems, enable a leap in maturity in operational safety.

At the same time, international organizations have consolidated good practices in electronic documentation for emergencies. The guidelines published under the European Agreement concerning the International Carriage of Dangerous Goods by Road, with emphasis on item 5.4.0.2 on electronic data interchange, encourage telematics and traceability. Although focused on the European scenario, these guidelines are technically compatible with the Brazilian reality when parameterized to local documentation and emergency response requirements, including the presence of an emergency response telephone number on transport documents and Safety Data Sheets for Chemical Products.

2 RISK FUNDAMENTALS APPLIED TO THE TRANSPORT OF DANGEROUS GOODS BY ROAD

Risk assessment in the transport of dangerous goods has historically combined the probability of an incident with the magnitude of the consequence. In road systems, a classic formulation calculates the risk of each road segment as the product between the probability of an accident with the release of a substance and the exposed population within an impact area, which varies according to the risk class of the product transported. This segmental risk is then aggregated along the route to compare alternative routes in a Geographic Information System, in order to select the one that minimizes the expected risk.

In recent years, two extensions have gained executive relevance. The first is the adoption of the Conditional Value at Risk as a metric of aversion to the cause of losses, which prioritizes the mitigation of extreme consequences, even if rare. The second is the incorporation of the principle of risk equity, which seeks to reduce asymmetries in the territorial distribution of risk, considering, for example, different emergency response times between municipalities or neighborhoods. In both cases, multiobjective formulations solved by optimization algorithms were proposed, including approaches based on multiple shorter paths and evolutionary heuristics.

3 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN PREDICTIVE RISK ASSESSMENT

In the predictive field, deep learning architectures that combine recurrent units with dense networks and multimodal embedded, have demonstrated the ability to integrate continuous telemetry variables, discrete operating variables, and even context images, producing risk classifiers in near real-time. Published evidence reports very expressive accuracy and area under the curve values, especially when models are trained with robustness techniques such as adversarial training, dimensional reduction, and prediction similarity checking to reduce sensitivity to noise and small samples.

The executive advantage of this approach is twofold. First, it generates a per-leg risk score that feeds directly into the risk-oriented routing module, updating conditional probability estimates when changes in weather, traffic, or construction work arise. Secondly, the explanation can be expanded by the parallel adoption of endogenous gradient models of the XGBoost type, useful to rank variables that are more influential in risk in each operational scenario, facilitating audits and technical conversations with regulators and insurers.

4 TELEMATICS, INTERNET OF THINGS, AND INTEGRATION WITH EMERGENCY RESPONSE

The deployment of sensors certified for explosive atmospheres in tank and valve assemblies – measuring pressure, temperature and vibration – combined with communications in narrowband networks for the Internet of Things and low-power long-range networks, enables continuous monitoring with very low alert latencies. Studies and technical reports highlight the usefulness of geof fences, pressure gradient alarms and safe stop strategies at points previously approved with the Fire Departments, which can be formalized in the Technical Instructions and in the internal response plans.

The digital document layer integrates the emergency response number required in many jurisdictions, the safety data sheet and the travel data, aligning with the international guidelines of item 5.4.0.2 for electronic data interchange. This integration streamlines the triggering and triage of critical information during an event and increases traceability for audit purposes.

5 APPLIED STUDY: CORRIDOR BR-116, KNOWN AS RÉGIS BITTENCOURT, FOCUSING ON CLASS THREE FLAMMABLE LIQUIDS

5.1 OBJECTIVE AND SCOPE OF THE STUDY

The executive objective is to demonstrate, in a critical national corridor, how the combination of predictive assessment, risk routing with Conditional Value at Risk and equity, and telemetry can reduce expected risk and extreme risk without jeopardizing delivery times. The scope includes Class three loads, with identification according to ABNT NBR 7500 and the presence of an emergency set in accordance with ABNT NBR 9735, in addition to operational protocols aligned with Technical Instruction 32 of 2025 of the São Paulo Fire Department.

5.2 TECHNICAL METHODOLOGY

The methodology comprises: (i) construction of a feature store with vehicle telemetry data, tank pressure and temperature signals, meteorological and construction data, and demographic layers to calculate impact areas by risk class; (ii) training of a deep learning model for risk scoring by stretch, validated with robustness techniques; (iii) optimization of routes by risk with multidisciplinary formulation minimizing expected risk, Conditional Value at Risk and territorial inequalities of risk, resolved by shortest multipath algorithm and heuristics; (iv) implementation of re-routing and safe stop policies, with digital activation of the emergency number.

5.3 INDICATIVE RESULTS AND DISCUSSION

In the planning, two route alternatives were compared: Route A, shorter, and Route B, approximately ten to twelve percent longer. Route B presented an expected risk of about twenty-two percent lower and a Conditional Value at Risk of approximately thirty-five percent lower, with a better territorial distribution of risk due to less passage through densely populated areas and with a longer response time. For repeat shipments, a mixed strategy was adopted seventy percent on Route B and thirty percent on Route A, which, according to the literature, reduces the exposure accumulated over time when there is uncertainty in the probabilities per segment.

In the execution, heavy rain events and construction work increased the conditional probability of an accident with release in urban segments, which triggered the automatic re-routing for Route B. In parallel, a pressure gradient higher than expected was detected in the tank's telemetry, triggering a safe stop at an approved point and the call of the emergency

number for triage and support, according to the best practices of electronic documentation and the response guidelines of the Fire Departments.

From an executive perspective, indicative gains include a reduction in expected risk between twenty and thirty percent and a reduction in Conditional Value at Risk to ninety-five percent between thirty-five and forty percent, preservation of delivery windows, document traceability for auditing, and increased risk equity. These numbers are in line with studies on risk assessment and optimization of risk-oriented routes in international contexts, adjusted here to the Brazilian regulatory environment.

6 IMPLEMENTATION, GOVERNANCE AND PERFORMANCE INDICATORS

The implementation can be carried out after evaluating the scenario presented individually, starting with a regulatory and data diagnosis to map risk classes, requirements of Decree No. 96,044 of 1988, ABNT standards and applicable Technical Instructions, followed by the construction of a minimum viable prototype of risk scoring and the coupling of the route solver by risk. The next phase includes telemetric instrumentation with certified sensors, the definition of geof fences and safe stop points and the formalization of table exercises with the Fire Departments.

For governance, it is recommended: (i) adoption of machine learning processes in production with monitoring of data drift and performance; (ii) publication of model sheets with explanations and limitations; (iii) periodic audits in accordance with Decree No. 96,044 of 1988, ABNT NBR 7500 and ABNT NBR 9735, and state Technical Instructions; (iv) executive metrics such as expected risk per tonne-kilometer, Conditional Value at Risk, territorial distribution of risk, telemetric alert latency and compliance index per trip.

7 LIMITATIONS AND FUTURE OPPORTUNITIES

Data quality is a critical factor. Incident databases may be underreported, and short historical series make it difficult to estimate the probabilities of rare events. Robustness, temporal validation, and active learning techniques mitigate some of these effects. In addition, regulatory acceptance is reinforced by models with greater explainability, audit trails and strict document adherence, aspects that favor dialogue with regulatory agencies and insurance companies.

As an opportunity, the convergence with smart city and green corridor programs stands out, which allow the integration of municipal traffic, meteorology and civil defense data into the decision ecosystem, in addition to deepening alignment with international guidelines for telematics and electronic documentation in emergencies.

8 CONCLUSIONS

The combination of predictive assessment based on machine learning, risk-oriented routing with a focus on controlling extreme events and territorial equity, and telemetry with electronic documentation, offers Brazil a pragmatic path to reduce risk in the road transport of dangerous products without compromising logistics efficiency. The case applied in the BR-116 corridor demonstrates the technical feasibility and normative adherence when the practices are based on Decree No. 96,044 of 1988, on ABNT standards and on the Technical Instructions of the Fire Departments.

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