ENHANCING THE TRANSPORT SAFETY THROUGH DISDROMETER-BASED ENVIRONMENTAL SENSING

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Resume

In this study is presented a system for real-time precipitation measurement integrating the laser disdrometer with adaptive control. The system manages large sensor data streams dynamically, enhancing robustness and accuracy under intense weather conditions. Meteorological inputs, combined with communication, enable scalable infrastructure supporting automated safety interventions. Experimental deployment showed improved data fidelity, anomaly detection, and detailed analysis of drop size and velocity distributions. The approach advances intelligent transportation safety and operational reliability through comprehensive environmental sensing and real-time adaptive data processing.

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1 Introduction

In the current geographical and climatic context, the accurate measurement of precipitation is considered essential for the safety and efficiency of transportation systems. The flow of traffic and the risk of accidents have been significantly affected by extreme weather events, including heavy rainfall and snowfall. Consequently, advanced meteorological measurement devices have been developed to provide precise and reliable real-time data to support decision-making processes in traffic management [1].

Modern optical instruments, such as the *Thies Clima Laser Precipitation Monitor*, are capable of detailed monitoring of raindrop size, velocity, and distribution. Compared to the conventional rain gauges, disdrometers provide enriched information on the characteristics of precipitation, which is critically important for transportation engineering when analyzing the impact of rainfall on pavement conditions, tire adhesion, and accident rates [2-3].

From a process control perspective, it is recognized that not only data acquisition from sensors, but also effective integration, processing, and adaptive control of these systems in real-time, are critical. Large volumes of data are generated by modern meteorological sensors, such as laser disdrometers, which require processing by advanced algorithms and cybernetic approaches for noise filtering, anomaly detection, and reliable estimation of precipitation parameters. The accuracy and robustness of measurements are enhanced by implementing adaptive regulatory mechanisms within sensor networks, which is fundamental for the real-time management of traffic systems.

The integration of meteorological sensors into intelligent transportation systems (ITS) has become increasingly important with the advancement of digitalization and IoT technologies. Contemporary road meteorological stations combine multiple types of sensors (temperature, humidity, wind speed, precipitation) and employ advanced communication protocols (4G/5G, Ethernet, RS-485, or RFID) to enable the prompt data transmission to centralized control systems. Such data processing facilitates weather forecasting and allows the automated activation of safety measures, such as dynamic speed limit adjustments or warnings about hazardous ice conditions [4-5].

Numerous studies have been conducted to evaluate the accuracy and reliability of laser disdrometers. Different optical disdrometer models have been compared, highlighting their capability to precisely capture raindrop size and velocity while acknowledging their limitations under extreme conditions such as very intense precipitation. Furthermore, significant research has focused on integrating meteorological data with traffic management systems to improve road safety and coordinating with broader environmental monitoring networks [6-9].

Challenges encountered within the sensor technology and cybernetics include the necessity for calibration, compensation for environmental influences, such as temperature and wind, and the mitigation of interference and signal loss under varying climatic conditions. These aspects are regarded as crucial for designing cybernetic systems with high reliability and autonomy in data acquisition units [10].

The objective of the presented research was to develop an optimized system for the automated collection and analysis of meteorological data using the *Thies Clima Laser Precipitation Monitor* for applications within intelligent transportation systems. The focus was on minimizing the measurement errors during high precipitation intensities, integrating the data into existing traffic control platforms, and evaluating the effects of environmental factors on data quality [11-12]. The expected outcomes are anticipated to contribute to enhanced safety and efficiency of transportation infrastructures under adverse meteorological conditions.

A distinctive feature of this study is the incorporation of adaptive cybernetic control mechanisms within the sensor networks for the real-time data processing and anomaly detection. This integration notably enhances the robustness and accuracy of the collected data. While prior research was predominantly concentrated on static sensor calibration, or isolated data processing techniques, this work focus was on the dynamic and autonomous management of information streams derived from sensors, thereby enabling more responsive and precise interventions in traffic management [13-15]. The research presents a holistic approach that combines advanced laser disdrometer measurements with multi-sensor meteorological inputs and IoT communication protocols. Such a comprehensive integration supports the development of a resilient and scalable infrastructure capable of executing automated safety responses, including dynamic speed regulation and hazard warnings, all driven by high-resolution environmental data. The novelty of this research is embodied in the synthesis of cutting-edge laser disdrometer technology, adaptive cybernetic control strategies, and intelligent transportation system applications. This synergy establishes a new standard in environmental sensing, aiming to enhance transport safety and operational efficiency.

2 Materials, methods, algorithms

The proposed system ensures automated collection, processing, and archiving of environmental data generated by a laser disdrometer. System components, including the system architecture, the mathematical model of the device, and the data component of the solution, are discussed in the following sections.

2.1 System architecture

The solution architecture integrates the sensor, communication, and software layers into a single functional unit that enables continuous monitoring of precipitation activity and subsequent data analysis. The block diagram of the system components is shown in Figure 1 and consists of four main blocks: *Disdrometer, RS-485 to Ethernet Converter, Server,* and a *Client*.

The measurement part of the system consists of a *Thies Clima Laser Precipitation Monitor*, a device designed to detect and classify atmospheric particles based on the principle of optoelectronic measurement. This principle uses a laser diode with a wavelength of 785 nm, situated in the infrared spectrum, to detect individual particles. An infrared transmitter (*IR Transmitter*) generates a collimated beam that passes through the measurement volume. On the other side, an infrared receiver (*IR Receiver)* records changes in radiation intensity. When a particle, such as a raindrop or snowflake, passes through, it partially shades the beam, which the *Control Unit* evaluates as a measurement event. The *Control Unit* subsequently digitizes the resulting signal, computes the relevant physical quantities (such as diameter, velocity, volume, and precipitation intensity), and stores them in a *FIFO Buffer*, serving as a memory cache. Data transfer to the higher communication level is ensured by the *RS-485 Interface*, which provides robust differential communication resistant to electromagnetic interference.

The RS-485-Ethernet converter *GNOME 485* from the company *Papouch* is used to connect the serial interface of the disdrometer to the network infrastructure. This module converts the data stream from the differential serial RS-485 format to the TCP/IP network protocol, enabling the integration of the device into a standard computer network without requiring hardware modifications. The converter supports configuration of communication parameters (speed, parity, IP address, port) and operates with the TCP, UDP, Telnet, HTTP, and DHCP protocols. In the proposed solution, it functions in TCP server mode, with the disdrometer periodically sending data to a defined port. The server layer represents the core of the system,

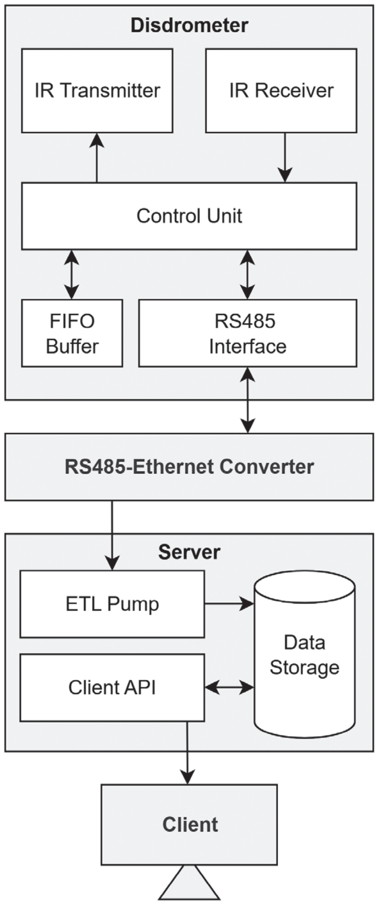

Figure 1 *Architecture of the proposed data acquisition system*

responsible for receiving, processing, and storing the data. The main software component is the *ETL Pump* (*Extract, Transform, Load*) implemented in Python:

Extraction (*Extract*) - Data are received via a network socket that maintains a persistent TCP connection with the converter. The received messages are processed as text strings and split into individual fields according to the protocol structure.

1. Transformation (*Transform*) - The data are decoded, validated, and converted into numerical values. During the transformation process, completeness checks, unit conversions, and timestamp validations are performed.
2. Loading (*Load*) - The processed data are stored in a non-relational database, which offers a flexible structure and allows easy extension with new types of variables without altering the database schema.
3. The server also provides data access through a client API, which enables visualization, export, and querying of historical data.

2.2 Mathematical model of disdrometer data processing

Based on the measured variables, specifically the diameter d and the fall velocity of individual particles, the disdrometer calculates several derived meteorological parameters [16]. Those parameters provide a comprehensive description of the precipitation event, enabling the classification of precipitation type, estimation of its intensity, and modelling of microphysical processes in the atmosphere.

The calculations are performed in the control unit according to a set of defined equations that form the mathematical data processing model. Among the most important derived variables are precipitation intensity, radar reflectivity, meteorological optical range (MOR), and other characteristics of the precipitation field.

The precipitation intensity I is calculated from the volume of all particles per unit time:

$$I = \frac{1}{A \cdot \Delta t} \sum_{i=1}^{N} V_i , \tag{1}$$

where A is the cross-sectional area, Δt is the measurement interval, N is the number of detected particles, and V_i is the volume of the i-th particle, expressed as follows:

$$V_i = \frac{\pi}{6} d_i , \tag{2}$$

where d_i is the diameter of the i-th particle.

Radar reflectivity represents the sum of the sixth powers of the diameters of all particles in the measured volume:

$$Z = \sum_{i=1}^{N} d_i^6 \, . \quad (3)$$

For comparability to meteorological radar measurements, reflectivity is often expressed on a logarithmic scale (dBZ):

$$dBZ = 10 \log(Z) \, . \quad (4)$$

Meteorological Optical Range (MOR) characterizes visibility, that is, the distance at which an object with a certain contrast edge can still be recognized. It is defined as:

$$MOR = \frac{3.912}{\beta} \, , \quad (5)$$

where β is the absorption coefficient (m^{-1}), calculated from the cross-sectional area of individual particles and their concentration in the measured volume.

2.3 Data structure and measurement processing

The data output of the disdrometer is implemented in the form of telegrams - structured data frames with a fixed format, containing a sequence of values representing physical quantities derived from the optoelectronic measurement principle. In this application, the following telegram types are utilized:

- *Telegram #3* provides microphysical data about individual particles, such as diameter, velocity, beam attenuation duration, and internal environment temperature.
- *Telegram #8* transmits aggregated meteorological indicators - precipitation intensity and total amount, radar reflectivity, visibility (MOR), and automatic weather type classification.

Since the disdrometer transmits data in discrete telegrams, the proposed system was designed to operate as a cyclic communication model that transitions between three defined operational states (Figure 2):

- *Short-term Measuring State* (*Telegram #3)* - continuous sensing of microphysical parameters of individual particles,
- *Long-term Aggregation State* (*Telegram #8*) - periodic collection and transmission of aggregated meteorological variables, and
- *Data Processing State* - validation, transformation, and storage of received data.

The *Short-term Measuring State* and *Long-term Aggregation State* operate in a blocking mode because they are limited by a single physical bus. Parallel to this is the *Data Processing State*, which is designed to avoid blocking the execution of further measurements.

Data processing is implemented as an ETL (Extract, Transform, Load) process [17]. In the *Extract phase*, data telegrams are received via a TCP/IP connection and decoded into a tabular structure, which serves as the basis for subsequent analysis. In the *Transform phase*, validation of values, format checking, calculation of supplementary parameters, and filtering of erroneous frames are performed. Since the disdrometer does not perform internal validation of data correctness, erroneous or physically improbable measurements may be transmitted. The basic measurement parameters - particle diameter d, its velocity v, and measurement time t, serve as reference variables from which all other microphysical and meteorological indicators are derived.

The filtering function f_{filt} formally defined as:

$$f_{filt}(d,v,t) = \begin{cases} 1, & v \in V_d \quad t < t_{now}, \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

where $V_d = \langle 0.2, 40 \rangle$ m/s represents the set of all allowable velocities that the disdrometer is capable of recording, $D_d = \langle 0.16, 5 \rangle$ mm determines the range of physically possible diameters of atmospheric particles and t_{now} is the current time during the data processing. Values outside these intervals are automatically discarded as invalid.

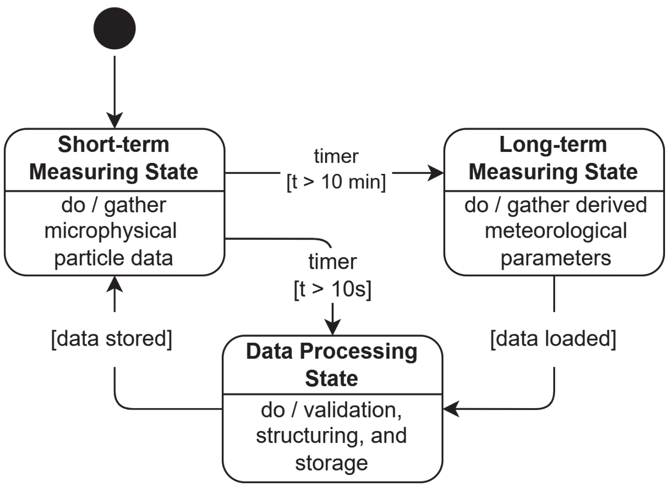

Figure 2 *State model of Measurement Processing*

Timestamps are then verified for consistency to avoid time jumps, duplicates, or data loss, ensuring the chronological integrity of the dataset. In the *Load phase*, processed data are stored in a time-oriented non-relational database (*InfluxDB*), which allows compact access to historical measurements and subsequent analytical processing. To reduce the database load, a local buffer with a capacity of 360 measurements (equivalent to one hour of data) is utilized, allowing for the batch insertion of records.

Cyclic switching between the measurement states ensures a balance between high temporal resolution and long-term data continuity. During the normal operation, continuous recording of *Telegram #3* occurs at 10-second intervals. Every 10 minutes, the system briefly switches to *Telegram #8* mode, receives aggregated data, and returns to the basic measurement state. Data integrity mechanisms have been implemented, including frame checks, automatic reconnection on errors, and timed delays during mode switches. Damaged or incomplete telegrams are automatically discarded to maintain dataset consistency.

3 Results

Within the framework of a pilot study, a system was deployed to collect environmental data, focusing on monitoring precipitation parameters, including daily totals, droplet size and velocity distributions, as well as their relationship to air temperature.

The test system was placed in a laboratory environment and used a *Raspberry Pi 5* as the main control and data collection node. Communication with the *Thies Clima Laser Precipitation Monitor*, connected to the university network, was conducted via a secure VPN connection.

Measurements were conducted continuously over a three-month period, during which millions of individual records were logged. For detailed analysis, the 41st calendar week of 2025 was selected, representing a typical pattern of autumn precipitation. During this period, 1,460,532 individual droplets were detected, which subsequently underwent filtering (see Equation (6)), validation, and visualization.

The average diameter of the recorded droplets was 0.35 mm ± 0.153 mm. The smallest detected droplets had a size of 0.16 mm, while the maximum value of 4.74 mm was at the boundary of the so-called "breakup limit" - the physical stability limit of raindrops. At this size, the droplet deforms due to air resistance and subsequently breaks apart into smaller particles. Droplets larger than 4.5-5 mm occur rarely in the atmosphere and typically correspond to short-term intense precipitation events.

The average terminal velocity of the particles was 1.716 ± 0.593 m/s, with a minimum value of 0.21 m/s and a maximum of 10.09 m/s. The size and velocity distributions of the droplets are shown in Figure 3.

The data were subsequently aggregated into hourly averages and used for analysis of the temporal course of precipitation intensity and air temperature (Figure 4). During the observed period, the temperature ranged from 9 to 16 °C, with an average value of 11.46 °C.

The velocity of raindrops in the range of 0.7-5 mm was analyzed through cluster analysis according to ambient air temperature to quantify its influence on droplet dynamics. The largest number of observations was concentrated in the cluster at the reference temperature of 10-11 °C, where a power-law dependence of velocity v on droplet diameter d was identified:

$$v = 3.663d^{0.676}\,. \tag{7}$$

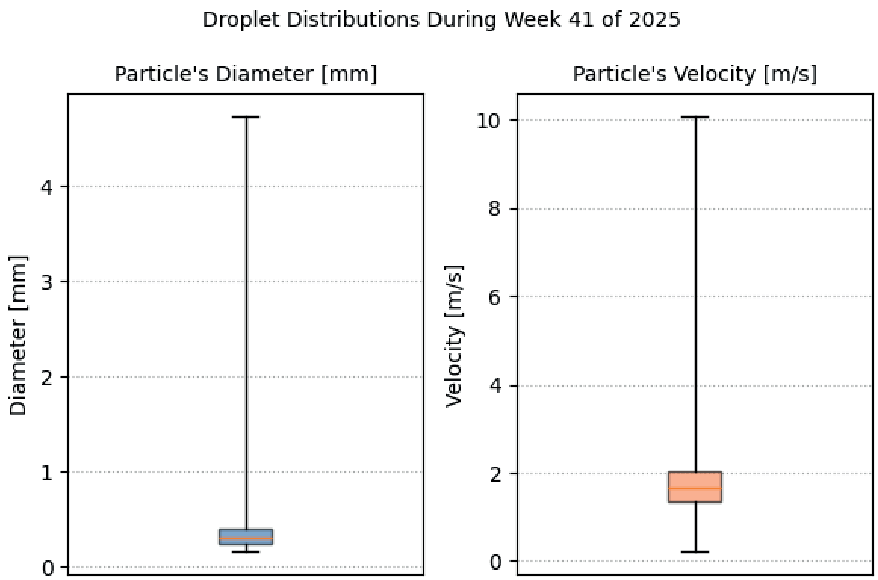

Figure 3 *Distribution of particle diameter and velocity displayed using a boxplot*

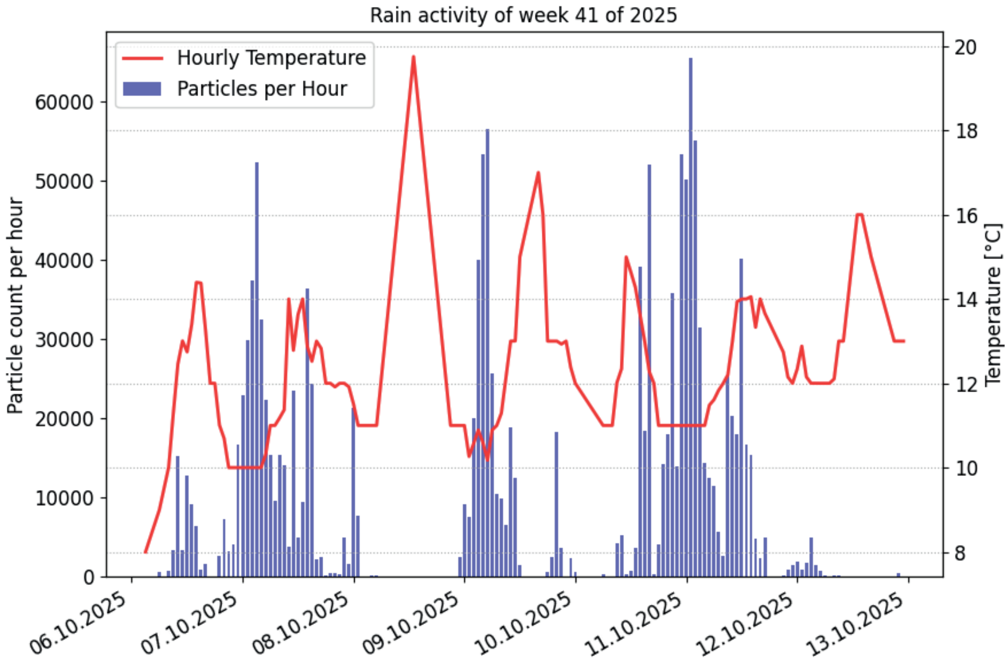

Figure 4 *Relationship between the temperature and a number of particles detected*

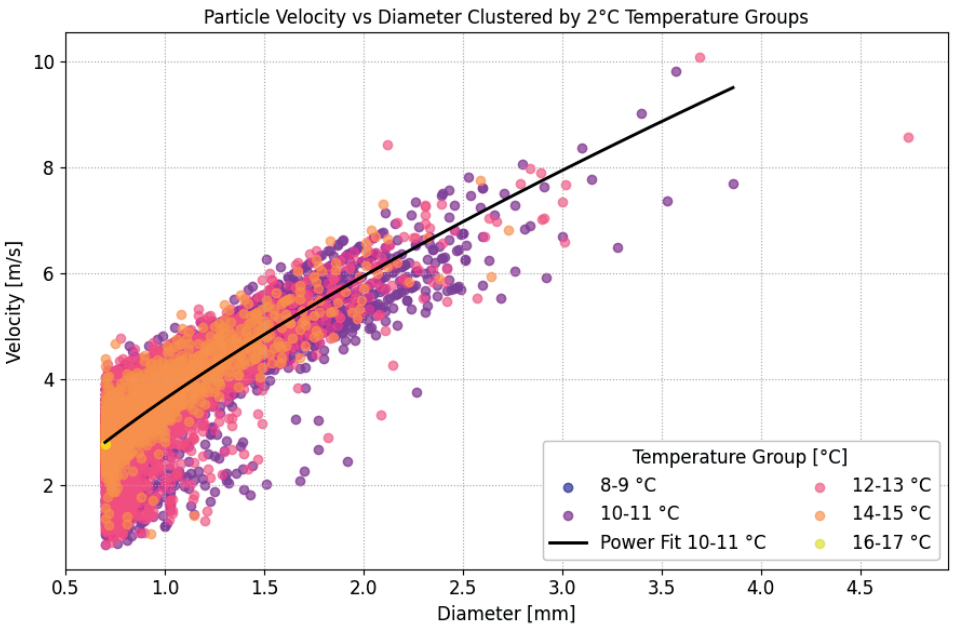

Figure 5 *Relationship between the particle velocity and its diameter*

Temperature did not significantly influence the relationship between the droplet velocity and diameter; the shape and parameters of the power-law function remained consistent across the individual temperature clusters. The results are shown in Figure 5.

4 Discussion

During the experimental period, the capability of the *Thies Laser Precipitation Monitor* to provide extensive and detailed information on precipitation characteristics, including particle size, velocity, and temperature, was confirmed. However, several technical and methodological limitations must be considered that may affect the accuracy and interpretation of the obtained data.

One of the main limitations is the device throughput during very intense precipitation events. According to the manufacturer's documentation, incomplete capture of falling particles may occur because *Telegram #3*, used for continuous measurement of individual particle parameters, has limited throughput under extreme rainfall density [16]. Data loss, however, is not directly detectable since the data stream remains high even with incomplete recording. Therefore, in short time intervals, the output may be slightly underestimated. Still, given the large number of recorded particles, this effect does not significantly impact the statistical values of overall precipitation parameters.

Another limitation arises from the constructional characteristics of the device. According to the technical department of *Thies Clima*, the disdrometer is not designed for dynamic switching of measurement modes during operation. The device is optimized for the long-term data transmission in a single telegram rather than periodic switching between different modes. The designed automated ETL system allowed switching between *Telegram #3* (raw particle data) and *Telegram #8* (processed aggregated data), thus obtaining a more comprehensive information set. However, this approach brings risks, particularly the potential damage or loss of data at the moment of switching, which was observed during measurements and corresponds to the expected system behavior.

In evaluating the measured data, focus was placed on particles with diameters ranging from 0.7 to 5 mm, although the technical range of the disdrometer begins at 0.16 mm. Particles smaller than 0.7 mm exhibited significant scatter, likely due to fog, dust, or other atmospheric particles dispersed by wind. The identified power-law dependence of velocity on droplet diameter corresponds to the expected theory of Stokes' equation, but further study is required for verification and quantification of this relationship. Additionally, the assumption that the disdrometer captures all the particles may lead to result bias; therefore, it would be appropriate to develop a more precise classification of atmospheric particles in the future.

Wind conditions may partially influence the measured velocity of precipitation particles at the measurement site. During the experiment, no wind shield or protective element was used to mitigate airflow effects. As a result, the measured droplet velocities may deviate from their actual terminal velocities, particularly in strong winds or near the sensor under turbulence. To address this limitation, it would be appropriate to complement the measurement system with an additional instrument, such as an anemometer, to quantify wind speed and apply corrections to the measured droplet velocities. In this study, data quality was improved only through a simple outlier filtering, particularly for droplets exhibiting abnormally high velocities, which were likely due to environmental conditions or measurement errors.

The results of this study indicate the potential for integrating adaptive control and advanced data processing in sensor networks for the real-time rainfall monitoring. Dynamic management of sensor data flows has improved measurement accuracy and robustness, especially under challenging weather conditions. The combination of laser disdrometer technology with advanced processing logic demonstrated clear benefits, while challenges remain related to environmental interference and ensuring sensor reliability during extreme climatic events.

Future research should focus on enhancing the multi-sensor data fusion, utilizing machine learning for anomaly detection, and developing decentralized processing architectures to minimize latency and improve system autonomy. Incorporating additional environmental parameters, such as fog density or road surface conditions, could further enrich the sensor framework. Moreover, extensive field deployments and long-term performance evaluations are crucial for validating the efficiency and sustainability of the system across diverse operational scenarios. This will contribute to development of smarter and more resilient transportation infrastructures, capable of proactively adapting to changing environmental conditions.

5 Conclusion

In this article, a system for collecting and processing environmental data (ETL), based on the *Thies Laser Precipitation Monitor* and *Raspberry Pi 5*, was proposed and implemented. This pilot study serves to verify the functionality and reliability of the designed system. The system demonstrated the ability to continuously collect and process detailed precipitation information, including the distribution of droplet sizes and velocities, while ensuring the reliable aggregation and visualization of this data.

The main contribution of the proposed solution lies in its ability to integrate the data collection, filtering, and processing into a single flexible framework, enabling robust precipitation monitoring even under challenging environmental conditions. Despite the presence of measurement errors, caused by extreme conditions - such as strong wind, fog, condensation on optical components, or snow, the system provides a consistent and high-quality dataset suitable for long-term trend monitoring and droplet distribution analysis.

Precipitation represents a key meteorological factor influencing the transport safety, particularly during extreme events, such as intense rainfall or snowfall. Such conditions can substantially reduce visibility, impair road surface adhesion, and increase the risk of aquaplaning or loss of vehicle control. Laser disdrometers not only measure rainfall intensity but also determine the droplet size distribution and velocity, providing more detailed information than conventional rain gauge systems. These data can support the detection of hazardous situations that pose direct risks to road traffic. Potential implementation scenarios include integrating precipitation measurements into the traffic management centers, where warning mechanisms could inform drivers via variable traffic signs or navigation applications. In a broader context, meteorological data from disdrometers could also support advanced driver-assistance systems or autonomous vehicle control.

The results presented in this article confirm that the designed ETL system represents an effective and modular tool for environmental monitoring, serving as a foundation for further development of intelligent sensor networks and real-time monitoring applications. For future implementations, a more stable software realization and cross-validation with alternative sensors are recommended to more precisely quantify the impact of environmental factors and minimize data loss.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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