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- Industrial Safety
- Mechanical Engineering Technology
- Mining
- Mechatronics

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## NANOCOMPOSITE MATERIALS FOR FUNCTIONAL COATINGS OF AUTOMOTIVE AND TRACTOR MACHINERY PARTS

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**Abstract.** The prerequisites and mechanisms of manifestation of the special energy state of the components of materials and metal-polymer systems, which determines the course of the specified processes in interphase interactions with the formation of boundary layers with optimal structure, are considered. The model of the spline joint of the cardan shaft, containing a coating of polymeric material, which allows to assess the factors that determine the stability of the material or coating to technological or operational influences. Criteria for selecting functional components of coatings based on aliphatic polyamides used in the construction of spline joints of cardan shafts are proposed. Nanocomposite materials based on industrial thermoplastics with increased parameters of performance characteristics for functional products (coatings) used in automotive and tractor machinery have been developed.

**Keywords:** nanocomposite material, metal-polymer system, functional coating, cardan shaft, spline joint, automotive and tractor machinery.

### 1. Introduction

In the designs of modern automotive and tractor machinery, elements made of functional composite materials based on polymer matrices are widely used. Thus, the optimal choice of the design solution, as well as the composite materials for the manufacture of cardan transmission elements, largely determine the technical, economic and operational characteristics of the machines and the effectiveness of their practical application [1].

One of the nodes of the cardan transmission, which determines the effectiveness of its use, is a spline connection that provides the process of functioning in dynamic changing load-speed modes and with constant axial movement of elements. To ensure the effective operation of the spline joint of cardan transmissions of various designs, composite materials on inorganic and organic polymer and oligomeric matrices are widely used, which provide high wear resistance in conditions of reverse motion and minimal losses for resistance to frictional forces [1]. In recent years, tribological coatings based on aliphatic polyamides (nylon, polyamide 6, Rilsan) have been widely used in cardan shaft structures, which reduce the intensity of corrosion-mechanical wear of the spline joint and reduce friction losses. To create such coatings, modern methodological approaches based on the use of functional modifiers of various composition and mechanism of action, allowing to purposefully change the structure of composites based on polymer matrices to ensure the implementation of the phenomenon of a low-wearing metal-polymer system [2].

Among the most promising areas for the creation of polymer composites with an optimal structure is the implementation of the nanostate of components, which allows the use of energy parameters to form stable bonds that ensure resistance to the effects of operational factors [3].

The purpose of this work was to develop criteria for the selection of functional components of coatings based on aliphatic polyamides used in cardan shafts.

## 2. Research methodology

Thermoplastic polymers were used as binders to obtain composites – polyamide 6 (PA 6), polyamide 11 (PA 11), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polytetrafluoroethylene (PTFE) and thermoplastic elastomers – thermoplastic polyurethane (TPU), ethylene-vinyl acetate (EVA) copolymer, divinyl styrene thermoplastic elastomer (DST).

As the main objects of research, nanodisperse particles of carbon-containing (graphite, ultradispersed detonation diamond (UDD), shungite, carbon fibers), metal-containing (oxides, salts of organic acids) and silicon-containing (mica, tripolite, opal, clay) compounds obtained by technological effects on natural and synthetic semi-finished products produced at industrial enterprises of Belarus, Russia and Uzbekistan were selected. Nanoscale particles were obtained by mechanical crushing and heat treatment of dispersed semi-finished products at temperatures of 673–1473 K.

Polymeric materials were used in the state of industrial supply in the form of granules or powder obtained by cryogenic dispersion of granules at a temperature of 87 K.

The parameters of the structure and characteristics of nanocomposite materials and products from them were investigated using modern methods of physical and chemical analysis: IR transmittance spectroscopy and IR spectrometry of multiply frustrated total internal reflection (Tensor 27, Bruker), X-ray diffraction (DRON 3.0), differential thermal analysis (Q-1500), optical microscopy (MF-2), scanning electron microscope (ISM-50A) and atomic force microscopy (Nanotope III). The energy state of nanomodifiers and composite materials was assessed according to the electron paramagnetic resonance (EPR) spectra and spectra of thermally stimulated currents (TSC) at the original apparatus of the V.A. Belyi Metal-Polymer Research Institute of National Academy of Sciences of Belarus. The dielectric characteristics (energy state) of materials after energy exposure (laser, ionic, temperature) were determined according to standardized methods.

**3. Results and discussion**

All types of interfacial processes in various types of contact interaction of components of materials or structural elements (systems) in the formation and operation of products of a certain functional purpose in machines, mechanisms, technological equipment used in various industries are due to the transfer of energy with the formation of a stable thermodynamically advantageous equilibrium state for specific conditions [4]. Multicomponent materials (plastics, composites, alloys), products and structures manufactured with their use are systems whose parameters (deformation-strength, tribological, thermophysical, operational, etc.) depend on the intensity of interphase interactions that determine the course of certain physical and chemical processes in boundary layers with a given intensity and lead to the formation of boundary layers of a given composition, structure and parameters characteristics [2]. For composite materials, the boundary layer parameters determine the aggregate parameters of the service characteristics of the products. In tribosystems, the boundary layer determines the mechanisms and kinetics of friction and wear processes and performs the function of the so-called "third body" separating the contacting components of the tribological system [1–3].

The processes of interfacial interactions lead to the transformation of the initial state of the components of systems (both static and dynamic), causing the achievement of the necessary parameters of strength, wear resistance, corrosion resistance, adhesive strength, heat resistance of the product or structure (systems of various composition, structure and functional purposes) [5]. In the interphase interaction of the components of the system, a complex of physical, physicochemical reactions with a predominance (prevalence) of one or several simultaneously takes place, for which the most favorable conditions are realized, determined by the value of the activation energy parameter.

To ensure the specified parameters of the processes of interfacial interaction during the formation of a boundary or separating layer with a structure adequate to the operating conditions of the system, it is necessary to establish a determining (prevailing) reaction in the contact zone and thermodynamic conditions for its flow at a given speed (kinetics). Such a prevailing (isolated) reaction, the kinetics of which corresponds to the conditions of formation or operation of the system, is a factor determining the stability of the material, product or structure to the effects of technological or operational factors [2, 3, 5].

Of particular importance are the noted aspects in the interaction of metal-polymer systems including a composite coating. To assess these factors, consider the model of the spline connection of the cardan transmission containing a coating of polymeric material.

The technology of applying polymer coatings is quite complex and requires the use of special methods of surface preparation and strict observance of temperature regimes [1].

To determine the technological parameters for the formation of a functional coating on the facejoints, an estimated calculation of its thickness was carried out, which is necessary and sufficient to ensure the specified conditions for contact interaction. The problem of determining the thickness of the polymer coating *h*, at which the alignment of contact stresses occurs, was solved under the assumption that the rigid coating is applied to the elastic base (Fig.).

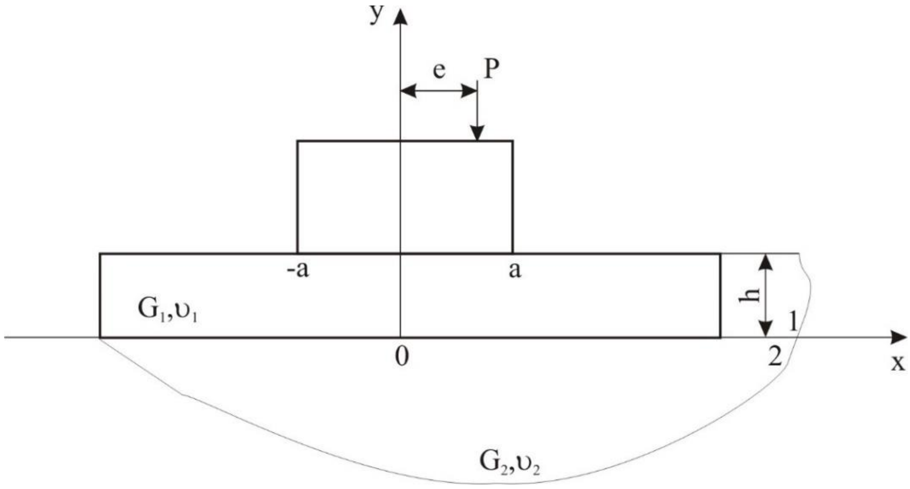


**Fig. 1.** Diagram of loading in the slotted joint of the cardan transmission in the presence of a polymer coating

Let the elastic half-plane surface ($y<0$) with characteristics $G_2$, $\nu_2$, be reinforced along the entire boundary ($y=0$; $|x|<\infty$) by a thin layer $h_c$ characteristics $G_1$, $\nu_1$. Consider the problem of frictionless alignment by force *P* with the eccentricity of application *e* to the upper boundary of the thin composite base of the stamp with a 2*a* width, the shape of the base of which is described by the function $y = g(x)$ [6].

Let's write down the boundary conditions of the problem in the form of:

$$\text{at } y=h;\ (1) \quad t_{xy}^{/} = 0(|x| < \infty); \sigma_y^{/} = 0; (|x| > a) \tag{1}$$

$$\nu 1 = -[\delta + dx - q(x)] \quad (|x| \leq a)$$

$$\text{at } u=0; \quad \sigma_y^{x/} = \sigma_y^2;\ \tau_{xy}^{x/} = \tau_{xy}^2;\ \nu_1 = \nu_2;\quad U_1 = U_2 \tag{2}$$

The tension at infinitely distant points are taken to be zero. In expression (1), the $\delta+dx$ function characterizes the rigid movement of the stamp under the action of the applied force *P* and the moment $P_e$.

Let's assume that the attitude

$$h/a \le 0{,}2 \text{ и } n=\theta_1/\theta_2=O(\frac{a}{h});\ \theta_1=G_1(1-\nu_1)^{-1};\ i=1{,}2$$

Then the polymer coating can be modeled with an overlay [6] described by the equation:

$$2G_1hU_1^{//}= -(1-\nu)(\tau_1-\tau_2)-0{,}5\,\nu_1h(\sigma_1+\sigma_2^{/})$$

$$\nu_1(x,h)-\nu_1(x,0)=0;\ \sigma_1-\sigma_2=0, \qquad (3)$$

где $\tau_1=\tau_{xy}^{/}(x,h)$; $\tau_2=\tau_{xy}^{/}(x,0)$; $\sigma_1=\sigma_y^{/}(x,h)$; $\sigma_2=\sigma_y^{/}(x,0)$, and the strokes ( $^{/}$ ) indicate derivatives in $x$.

Using formula (3), boundary conditions (1) and (2) can be given the form:

at $y$=0; $$2G_1hU_2^{//} = (1-\nu_1)[\tau_{xy}^2-\nu_1h(\sigma_y^{//})]^2$$

$$\sigma_y^2=0;\ (/x/>a);\ \nu_2=[-\delta+dx-q(x)],\quad (/x/\le a)$$

The half-plane stresses at $x^2+y^2\to\infty$ disappear. Using the Fourier transform, the problem in question can be brought to an integral equation with respect to the contact pressure distribution function:

$$\int_{-a}^{a} q(\xi)k\frac{(\xi-x)}{2nh}d\xi = \pi m\Theta_2+[\delta+dx-q(x)];;$$

$$k(t)=\int_0^\infty \frac{u+m}{u(u+1)}\cos utdu;$$

$$m=n(\xi n-\eta\mu)^{-1};\xi=0{,}25(3-4\nu_2)(1-\nu^2)^{-2}$$

$$\eta=0{,}25(1-2\nu_2)(1-\nu_2)^{-1}$$

Based on the assumptions made and the results obtained, it can be shown that the thickness of the polymer coating ($\theta_1 << \theta_2$) should be determined from the condition $h>>d$, where $d$ is the diameter of the contact spot. Using the data of the work [7], it can be concluded that the thickness of the polymer coating should be $h\ge$ 0.1 mm (100 μm). The closer the values *of* $G_1$, $\nu_1$, the smaller the thickness of the coating.

During the operation of a metal-polymer system, the polymer coating is subjected to a complex effect of factors leading to its corrosion-mechanical wear. Therefore, the most important condition for the formation of a coating with high parameters of operational characteristics is the establishment of a prevailing physical and chemical reaction that determines the mechanism of wear during friction without the supply of external lubricant.

The establishment of the prevailing physicochemical reaction, which determines the kinetics of wear of metal-polymer systems during their operation without external lubrication, made it possible to propose various directions for regulating its kinetics and create conditions for the formation of a boundary separating layer with the properties of an anti-wear component – a wear inhibitor – in the zone of frictional contact [2, 5].

The mechanism and kinetics of physicochemical reactions occurring with the transfer (exchange) of energy of components during their static and dynamic contact determine energy processes. For a stable and directional (regulated) course of the isolated (determining) physicochemical process in the interphase interaction of components with a given intensity, it is necessary to achieve their total energy of the activation energy value under certain conditions of the system's existence.

In accordance with modern ideas about the kinetics of interphase interactions [2–5], the most important parameter for the formation of a system of various composition, structure and purpose, determining the conditions for achieving its optimal structure, is the energy state of the components.

To characterize the energy state of the components, we will use a complex parameter, which is the cumulative result of the transformation of the initial individual parameters (structure, composition, morphology, size) under the influence of technological and operational factors, which is correlated with the value of the activation energy of the selected process of a certain mechanism and kinetics in the interphase interaction and expressed in physical units.

System analysis of the mechanisms for realizing the energy state of components [2, 5, 8] made it possible to establish a functional relationship between the system parameters in the formation of the energy factor of materials science and the technology of systems of various structures – composites, metal-polymer units and structures, including tribological ones. The main task of creating composites and metal-polymer systems with specified parameters of operational characteristics is to form boundary and separating [5] layers with optimal structure parameters. To form metal-polymer systems with specified parameters of operational characteristics, it is necessary to intensify the determining (prevailing) interfacial reactions in the creation of functional composite materials based on high-molecular (polymer, oligomer and combined) matrices and metal-polymer systems (static and dynamic – tribological) by implementing a special state of components, which according to the formed the conceptual apparatus is called nanostate [9–12].

The analysis of the prerequisites for the formation of the nanoconstitution of components of materials based on high-molecular matrices and metal-polymer systems made it possible to develop directions for their practical implementation. Methodological principles for obtaining nanocomposite materials based on industrial thermoplastics have been developed, consisting of:

– established crystal and chemical prerequisites for the selection of natural and synthetic carbon-containing, metal-containing and silicon-containing semi-finished products for the directed formation of active nanoscale particles with specified structural, morphological and energy parameters with optimal technological effects (mechanical, mechanochemical, thermal, laser);

– implementation of the conditions of energy compliance of nanomodifiers with the prevailing mechanism for the formation of the optimal structure of polymeric, oligomeric and combined matrices at various levels of organization – molecular, supramolecular and interphase in a given temperature range;

– providing conditions for the manifestation of the preferred mechanisms of interphase physicochemical interactions of components with the formation of boundary layers of optimal structure, determining the mechanisms of destruction of nanocomposites and wear of metal-polymer systems under the influence of various operational factors.

The developed methodological approaches for assessing the role of the phenomenon of nanostration of composite modifiers and metal-polymer systems were tested [3, 13–19].

For the manufacture of sealing, protective and damping elements of automotive units (brake chambers, automotive shock absorbers, cardan shafts), compositions of nanocomposite materials based on thermoplastic elastomers (EVA, TPU) modified with thermoplastic components (HDPE, FDO (copolymer of formaldehyde and 1,3-dioxolane)) in combination with nanoscale particles (NSP) of silicate-containing minerals of a layered, frame or chain structure obtained by heat treatment of dispersed semi-finished products have been developed.

The introduction of silicate NSP into the matrix ensures the formation of transition layers at the interface "thermoplastic elastomer – thermoplastic polymer" by the mechanism of adsorption interaction of macromolecules of the matrix binder and modifying component with the active centers of the dispersed particle, which performs the function of a physical catalyst. By changing the ratio of the polymer and nanoscale modifier, it is possible to adjust the parameters of the deformation-strength characteristics and abrasion resistance of composite products (membranes, protective casings, damping elements).

Another embodiment of the abrasive-resistant nanocomposite material based on polyolefins (PP, HDPE, LDPE) is the use of mechanized particles of natural silicates, which have increased activity in the processes of adsorption interaction with the macromolecule. The action of the uncompensated charge in the particles of the modifier determines the orientation processes in the melt of the composite with the formation of ordered (quasi-crystalline) structures that play the role of reinforcing nanoblasts. An additional effect of hardening and increasing the abrasive resistance of composites is achieved with orientation single-axis extraction of the semi-finished product in the form of a strand, followed by the introduction of reinforcing elements into the base matrix (PP, LDPE, HDPE). The use of silicate NSP for the modification of polyolefins makes it possible to adjust the parameters of rheological and stress-strain characteristics in a wide range.

To increase the operational life of heavily loaded friction units of automobile units and technological equipment (cardan shafts, lathe cartridges), compositions and technology of nanocomposite materials based on polyamides have been developed. Modification of the polyamide matrix (PA 6, PA 11) of silicate minerals (mica, montmorillonite, kaolin, tripolite) NSP causes the achievement of the necessary adhesive characteristics of the coating with a significant increase in their wear resistance during operation without external lubrication. The developed patented tribological compositions are an effective alternative to compositions based on the imported analogue of PA 11 ("Rilsan").

Metal-polymer nanocomposite coatings based on polymer binders, obtained when exposed to thermal gas flow on a mixture of thermoplastic polymer (PA 6, HDPE) and metal-containing precursor (formates, oxalates, carbonyls of Cu, Zn, Ni, Fe), are characterized by increased wear resistance, adhesive strength and resistance to thermooxidizing media [19].

To develop composite materials for the application of tribological coatings, polymer thermoplastic matrices produced in multi-tonnage were used, including by domestic manufacturers – PA 6, HDPE, PP. Modification of matrix polymers with functional components (tripolite, flint, kaolin, HDPE) was carried out by mechanochemical activation (MCA) with subsequent grinding at cryogenic temperatures (87 K). Coatings were formed by the method of fluidized layer using the original apparatus of the V.A. Belyi Metal-Polymer Research Institute of National Academy of Sciences of Belarus. Comparative studies (Table) indicate that the developed compositions are not only not inferior to the imported analogue of PA 11 ("Rilsan", France), but also significantly superior to it in wear resistance. At the same time, the compositions of composite materials developed on the basis of polyamide 6 (JSC Grodno Azot, Belarus) have a cost 3–5 times lower than the imported analogue.

**Table 1.** Characteristics of nanocomposite materials for tribological coatings

| *Characteristic* | *Parameter for material* | | |
|---|---|---|---|
| | *PA 11 "Rilsan", France* | *PA 6, JSC «Grodno Azot»* | *Developed composition* |
| *Tensile stress, MPa, not less than* | *43* | *50* | *67–78* |
| *Adhesive strength, cm, not less than* | *20* | *15* | *27–32* |
| *Brinell hardness, MPa* | *90* | *100* | *89–94* |

| | | | |
|---|---|---|---|
| *Coefficient of friction* | *0.05–0.20* | *0.15–0.25* | *0.10–0.15* |

Compositions of materials with MCA components have been successfully tested in the designs of cardan shafts of trucks, lathe cartridges produced at JSC "Belcard" and JSC "BelTAPAZ" (Grodno, Belarus).

## 4. Conclusion

On the basis of a systematic approach to the study of the influence of the features of the structure and energy state of nanoscale particles of condensed matter, the mechanisms of physicochemical processes in polymer matrices are proposed, determining the parameters of their structure at the molecular, supramolecular and interphase levels. Methodological approaches to the creation of nanocomposite machine-building materials with increased parameters of deformation-strength, tribological, adhesive and protective characteristics based on industrial thermoplastics and technology of their manufacture and processing into products.

Functional nanocomposite materials with high parameters of stress-strain, tribological, adhesive and protective characteristics based on industrially produced thermoplastics (polyolefins, polyamides, polyurethanes) and technologies for their manufacture and processing into products used in automotive and tractor machinery have been developed.

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# Algorithmic support for incident detection by stationary transport detectors in the Intelligent Transportation System (ITS) of a metropolis.

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**Abstract:** It is widely recognised that, in addition to the Automated Traffic Management System developed for urban areas, there is a range of techniques and systems for automated traffic management that are specifically designed for suburban or 'access' highways and motorways. This text describes navigation systems and other technologies that involve equipping vehicles with specialized equipment. It also includes various subsystems, such as technical, algorithmic, mathematical, ergonomic, financial, and legal, which are responsible for ensuring the functionality and advancement of automated systems. Intelligent transport

systems integrate various components to regulate traffic, including incident detection methods and setups for traffic accidents.

Incident detection algorithms can be categorized as automatic or non-automatic. Automatic algorithms rely on traffic flow condition data acquired from transportation detectors, while non-automatic algorithms rely on eyewitness reports. The article examines the methodologies used to gather data for incident detection algorithms, which are currently dominated by the use of data from stationary traffic detectors. It focuses on the detection of incidents on highways using stationary transport detectors, scrutinizing existing and potential algorithms. These detectors are used in automated traffic management systems and are part of the development of intelligent transportation systems in cities, metropolises, and regions. The goal is to integrate current algorithms into automated traffic management systems, along with modern vehicle technology, including autonomous technology, and connect them to 'smart' transport infrastructure to create a comprehensive and intelligent transport environment.

**Keywords:** Automated Traffic Management System, Intelligent Transportation System, algorithmic support, incident detection algorithm, stationary transport detectors.

## Introduction

Algorithms designed for incident detection can be broadly classified into two primary categories when considering automation: automatic and non-automatic incident detection [61, 62, 63, 65]. Automatic algorithms pertain to those specifically engineered to autonomously identify incidents by utilizing data derived from transport detectors, which reflects the traffic flow's condition. Conversely, non-automatic algorithms or procedures depend on information provided through reports from human eyewitnesses [64, 65].

Based on functional characteristics, incident detection algorithms are divided into algorithms for highways and algorithms for street networks [1, 2, 3].

Based on data acquisition methods, incident detection algorithms are divided into three groups:

- algorithms using data from stationary vehicle detectors (inductive loops, radars, video cameras, etc.).

- algorithms using mobile sensors (Bluetooth, wifi, RFID, GPS, GLONASS sensors, toll system transponders, etc.).

- algorithms that use information from drivers (GSM communications, navigation services, Internet applications, etc.)

This review discusses algorithms that use data from stationary vehicle detectors.

The disadvantages of incident detection algorithms using stationary vehicle detectors include:

1. The need to install and operate vehicle detectors (inductive, video, etc.) leads to interference with traffic flow and sometimes to temporary closure of traffic;
2. The location of installation of vehicle detectors, the frequency of their installation and the number are critical from the point of view of detecting an incident on a particular section of the highway. However, it is extremely labor- and capital-intensive to install stationary detectors along the entire length of the highway.
3. Inductive vehicle detectors, which are mainly used to determine the parameters of traffic flows on highways, are unreliable and often fail, which makes detection of incidents on a particular section of the road ineffective.

The advantages of the algorithms under consideration include their proven reliability and accuracy in identifying incidents over decades, which is their undoubted advantage over algorithms that use mobile sensors or information from drivers [4, 5, 8, 9].

## Method

The most commonly used algorithms for detecting incidents on highways are:

1. Comparative pattern recognition algorithms assume that an incident leads to increased traffic density upstream and decreased traffic density downstream. Examples of such algorithms include California TSC #7, #8, #10, APID, and PATREG.

2. By monitoring three basic traffic flow variables: speed, flow and lane occupancy (density), catastrophe theory algorithms are used to detect incidents. The algorithm detects an incident when there is a sharp drop in speed without an immediate corresponding change in occupancy and flow. An example of such an algorithm is the McMaster algorithm.

3. Statistics-based algorithms such as Autoregressive Integrated Moving Average (ARIMA), SND, and Bayesian algorithm are used to compare real-time traffic data with forecasted data, classifying unexpected changes as incidents.

Artificial intelligence algorithms are based on the recognition of visual patterns or classification.

An overview of video processing for traffic applications, covering traffic monitoring and automated vehicle control, is given in [43]. The paper discusses both fixed cameras (road monitoring) and moving cameras (autonomous vehicles) with specific examples of automatic lane detection and object detection. The paper examines eleven different traffic monitoring systems with static cameras. Among the systems reviewed, only Autoscope [26] remains a viable commercial product to date.

A video-based traffic state estimation method used for incident detection is proposed in [42]. The system estimates traffic intensity, speed, and density directly from video images. Incidents are identified based on the segmentation of the three-dimensional traffic state space using threshold values. The system has not yet been evaluated in real-world conditions. However, it represents an interesting model-based approach to incident detection that could be informative.

The authors addressed the challenge of extracting traffic information from uncontrolled, publicly available video streams in their study [46]. This is a significant problem from a broader machine learning perspective, as publicly available video streams can provide a wealth of information about traffic flow. Although primarily a review, the authors identified key challenges in using uncontrolled video for real-time traffic monitoring, including:

- Lack of control and information about orientation (angles of view, distance, etc.), complicating the mapping onto a logical network.
- Consideration of mismatches caused by occlusion and other factors.
- Fluctuating video quality.
- Influence of the environment, including weather and lighting effects.

The authors did not propose specific deployment steps; however, currently, systems utilizing public video are widely adopted due to the advancements in machine learning [11-25].

In the paper [41], a vehicle tracking system based on video is proposed. It relies on a turn-change detection algorithm that requires less calibration than existing systems. Experimental results using videos from the Las Vegas, Nevada area show favorable distinctions from the existing commercial Autoscope setup, based on ground truth measurements. The system has been deployed in a congestion alert system at construction sites and on highways during special events, although a performance evaluation for this application has not been provided.

In the paper denoted as [47], a comprehensive examination of the outcomes stemming from the "Realisation of an AID Enhanced Road traffic" (RAIDER) initiative is provided. This program received funding from a European consortium, comprising entities such as TNO from the Netherlands, AIT from Austria, TRL from the UK, and FEHRL from Belgium. Within this assessment, the AVID (Automatic Video Incident Detection) system is evaluated against three prospective variations of AID (Automatic Incident Detection) systems anticipated to emerge by the year 2030.

The initial system under scrutiny is eCall, wherein vehicles involved in road traffic incidents autonomously relay accident-related information to emergency services—a mandate in Europe since 2018. The second entails the utilization of mobile (floating) devices, wherein vehicles serve as passive sensors, furnishing Floating Car Data (FCD) utilized for AID. The third typifies cooperative systems wherein vehicles actively identify incidents in their vicinity and transmit these detections centrally.

Drawing from an analysis of prevailing technological capacities and anticipated advancements, the authors assert that "video-based vehicle tracking and radar-based scanning represent the sole detection technologies within the purview of this project capable of meeting the specified criteria for accident detection by 2020. These solutions should be perceived as interim measures until they are supplanted by onboard or mobile devices."

In the citation [48], a comparative analysis is conducted among various systems such as AUTOSCOPE, CCATS, TAS, IMPACTS, and TraffiCam, juxtaposing them against video-based vehicle tracking systems like CMS Mobilizer, Eliop EVA, PEEK VideoTrak, Nestor TrafficVision, Autocolor, and

Sumitomo IDET. The paper underscores the challenges faced by the latter systems in dealing with vehicle occlusion, highlighting the pivotal significance of camera placement.

Conversely, in reference [58], the authors introduce a real-time video surveillance system employing video analytics, specifically addressing the identification of stationary vehicles. This proposed system aims to resolve deployment-related hurdles, encompassing automatic calibration. The authors compare their system with an unspecified commercial product and advocate for a more comprehensive evaluation of their innovation. Nevertheless, the evaluation of the proposed system was notably limited as the testing scenario featured only one instance of a stationary vehicle, which was successfully detected.

The paper [52] proposes a method for evaluating traffic flow states, including intensity, speed, and density, in each lane. This is achieved by dividing the lanes into tracked cells and tracking objects through them. Incident occurrence conditions are determined using a fuzzy state vector mechanism to classify traffic flow states corresponding to incidents. The results are compared favourably with the California and McMaster algorithms, which use inductive traffic detectors. However, the authors acknowledge that their algorithm may be affected by external factors such as weather and lighting, as well as the field of view angle, which are common issues with video detectors.

In a similar solution proposed in [49], customizable video analytics are used to evaluate traffic flow intensity and speed. These assessments are then classified as incident or non-incident conditions using a fuzzy logic analyzer. It is recommended to perform manual calibration of parameters based on a specialized analysis of traffic speed data to ensure reliable results. The current system's results are likely to vary significantly depending on the deployment due to the lack of a more reliable calibration method.

In the paper [36], a video-based system is proposed that identifies traffic flow states using object detection and flow analysis model [66, 67]. The authors claim that the system can adaptively switch between learning and online modes based on the stability of the flow model [27-29]. The system was primarily used for evaluating traffic flow states, but the authors assert that it has applications for video incident detection.

## Results and Discussion

The effectiveness of a method or algorithm is evaluated based on standard parameters, including the Detection Rate (DR), Mean Time to Detection (MTTD), and False Alarm Rate (FAR) [10].

DR is calculated as the ratio of detected incidents to the total number of incidents, expressed as a percentage. It is important to note that the definition of an incident in the system affects this parameter. Therefore, it is crucial to have a clear definition of what constitutes an incident and what does not.

$$DR = \left(\frac{N_{DI}}{N_{TI}}\right) * 100 \quad (1)$$

where: $N_{DI}$ – the number of detected incidents; $N_{TI}$ – the total number of incidents.

Mean Time to Detection (MTTD) is defined as the time from the occurrence of an incident to the moment it is detected. This parameter does not include the time required to verify the incident (whether the incident indeed occurred).

$$MTTD = \sum_{i=1}^{N}(t_a - t_{inc})/n \quad (2)$$

where: N – the number of detected incidents; $t_a$ – the time when the incident was detected; $t_{inc}$ – the time when the incident occurred.

The False Alarm Rate (FAR) is determined as the percentage of incorrect detection signals relative to the total number of incidents.

$$FAR = \left(\frac{N_{FA}}{N_{TA}}\right) * 100 \quad (3)$$

where: $N_{FA}$ – the number of false alarms; $N_{TA}$ – the total number of alarms.

The performance of automatic incident detection algorithms is influenced by various factors [34], including but not limited to: The factors that affect traffic conditions include operational conditions (such as heavy, moderate, light, at capacity, or significantly below capacity), geometric factors (such as slopes, inclines, and descents), environmental factors (such as dry pavement, wet pavement, snow, ice, and fog), incident duration, incident severity, distance between detectors, incident location relative to the detection station, and traffic flow heterogeneity. Accounting for all the complex factors in a single algorithm is a challenging task, particularly in an arterial environment. None of the existing algorithms have been adapted to consider all these factors, and therefore, their effectiveness cannot be guaranteed for all road conditions. When studying the impact and effectiveness of incident detection algorithms related to geometry and incident characteristics [6], the results indicate that the choice of the tested California algorithms (Nos. 7, 8, and 10) significantly influences the detection rate (DR) and mean time to detection (MTTD). It is challenging to avoid the negative consequences of external factors [31-40].

In [32], algorithms are categorized into five types: pattern recognition, statistical processing, catastrophe theory, artificial intelligence, and video analytics (refer to Table 1).

Table 1 - Comparison of the effectiveness of algorithms based on data from inductive loops and video detectors [32]

| *Algorithm Type* | *Algorithm* | *Detection Rate (DR)* | *False Alarm Rate (FAR)* | *Mean Time to Detection (MTTD)* |
|---|---|---|---|---|
| *Pattern Recognition* | *California No. 7* | *67%* | *0.13%* | *2.91 min.* |
| | *APID* | *86%* | *0.05%* | *2.55 min.* |
| *Statistical processing* | *SND* | *92%* | *1.3%* | *1.10 min.* |
| | *Bayesian algorithm* | *100%* | *0%* | *3.90 min.* |

| | | | | |
|---|---|---|---|---|
| | *ARIMA* | *100%* | *1.4-2.6%* | *0.39 min.* |
| | *Smoothing models* | *92%* | *1.87%* | *0.74 min.* |
| | *DES* | *82%* | *0.28%* | *5.05 min.* |
| | *HIOCC* | *96%* | | |
| | *Filtering models* | *95%* | *1.5%* | *0.67 min.* |
| | *Dynamic Models* | | *less 0.02%* | *Short* |
| *Catastrophe Theory* | *McMaster Algorithm* | *100%* | *0.04%* | *1.5 min.* |
| *Artificial Intelligence* | *Neural Network Model* | *97%* | *0.21%* | *2.83 min.* |
| *Video Analytics* | *INVAID-TRISTAR* | *90%* | *1 every 3 hours* | *0.33 min.* |

In the study [30], the effectiveness was evaluated using a sensitivity analysis of the most common traditional automatic incident detection algorithms and the proposed Minnesota algorithm. Three types of algorithms were compared qualitatively and quantitatively: comparative logic (i.e., a series of California algorithms), statistical forecasting (i.e., standard deviation algorithm, double exponential algorithm, ARIMA algorithm, and HIOCC algorithm), and macroscopic traffic analysis (i.e., the McMaster algorithm, dynamic algorithm, and dummy traffic volume algorithm). They found that the investigated algorithms have several limitations related to: 1) unsatisfactory quality of raw data (i.e., data from inductive detectors) and the use of raw data only with limited filtering; and 2) the inability to distinguish incidents from bottleneck clusters or other similar road situations. The best algorithms in comparative logic and time series types were selected based on DR-FAR curves and compared with the Minnesota algorithm using a dataset collected in Minneapolis, Minnesota. The performance comparison figures, DR-FAR curve, and TTD histogram are shown in Figures 1 and 2, respectively. In Figure 2, negative TTD values are due to "0" being the time when the operator determines that an incident has occurred. However, if the operator has determined it, then an algorithm that takes more time is not required.

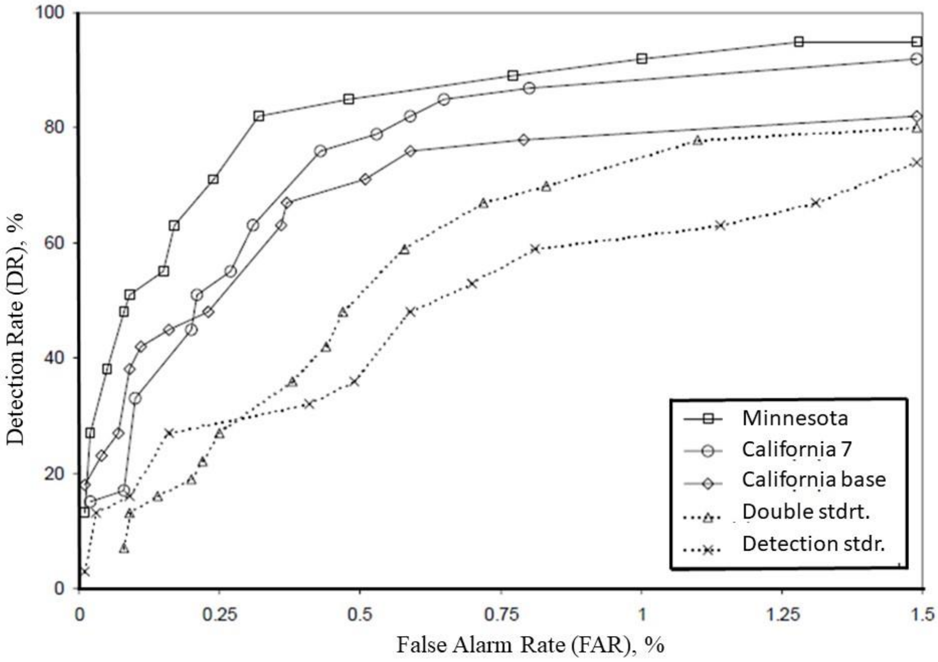


Figure 1. Comparison of algorithms based on DR-FAR parameters [30]

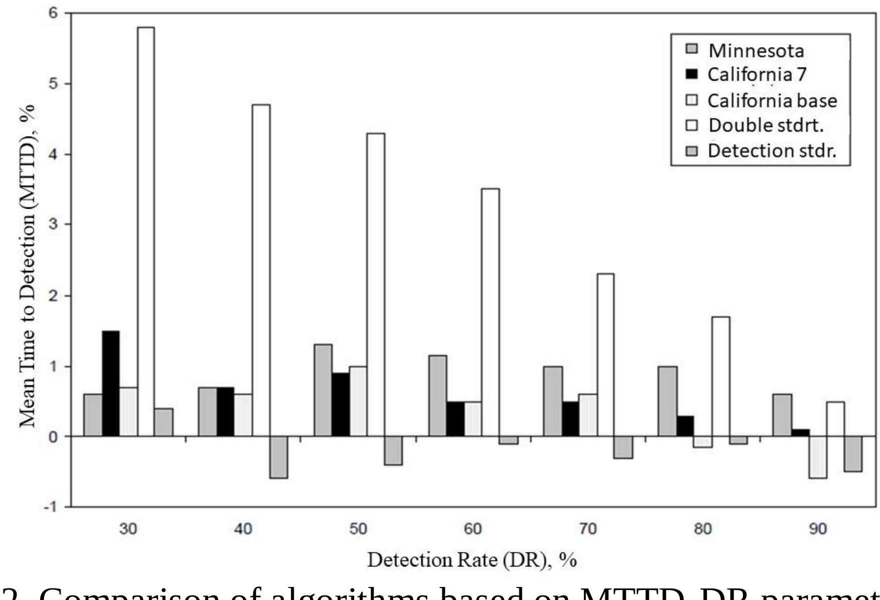


Figure 2. Comparison of algorithms based on MTTD-DR parameters [30]

The author concludes, based on these assessments, that raw inductive loop detector data often proves unsuitable for incident detection if the noise in traffic flow parameters cannot be filtered out before use. In particular, this is a limitation characterizing comparative algorithms, as the distortion caused by the noise makes it difficult for the algorithm to detect "patterns" of incidents in traffic flow data.

Similarly, fluctuations created by noise sources can be mistaken for incidents. As a result, the only easily identifiable "patterns" (templates) in traffic flow are those that occur under conditions of severe incidents and satisfy every algorithm test. As for statistical forecasting algorithms, they use filtering according to their design specifications, so their applicability is severely limited. The main drawback of these algorithms lies in their inability to distinguish incidents from similar traffic flow "patterns" (templates) [75, 76, 77].

In the work [7], the author evaluated a variety of common incident detection algorithms based on theory and practice. The algorithms were assessed in terms of their performance, data requirements, implementation simplicity, calibration simplicity, and operational experience [68, 69]. The algorithms were classified into one of five groups: comparative algorithms, statistical algorithms, time series algorithms, smoothing or filtering algorithms, and modeling algorithms. The results of theoretical assessments and on-site research showed that: 1) most freeway management centers used a modified version of the California algorithm, except for Toronto, where a different algorithm was used; 2) operators generally did not heavily rely on automatic incident detection algorithms; 3) for the most part, operators relied on other mechanisms, such as radio broadcasts or video monitoring (CCTV), to alert them to incidents on the freeways; and 4) among the systems that discontinued using the algorithm, incorrect calibration was the most common reason why algorithms generated a large number of false alarms. Moreover, it was considered that algorithms could not be properly calibrated if an incident did not affect every detection zone [71, 72, 73, 74].

Table 2 – Comparative analysis of algorithms based on data from inductive detectors [7]

| *Algorithm Type* | *Algorithm* | *Detection Rate (DR)* | *False Alarm Rate (FAR)* | *Mean Time to Detection (MTTD)* |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| *comparative* | *California basic* | *82%* | *1.73%* | *0.85 min.* |
| | *California No. 7* | *67%* | *0.134%* | *2.91 min.* |
| | *California No. 8* | *68%* | *0.177%* | *3.04 min.* |
| | *APID* | *86%* | *0.05%* | *2.5 min.* |
| *statistical* | *SND* | *92%* | *1.3%* | *1.1 min.* |
| | *Bayesian* | *100%* | *0%* | *3.9 min.* |
| *time series* | *ARIMA* | *100%* | *1.5%* | *0.4 min.* |
| *smoothing or filtering* | *DES* | *92%* | *1.87%* | *0.7 min.* |
| | *LPF* | *80%* | *0.3%* | *4.0 min.* |
| *flow modeling* | *McMaster* | *68%* | *0.0018%* | *2.2 min.* |

The work [45] provides a comparison of classical algorithms, a video analysis algorithm and an algorithm using cell phone data. Although the algorithms are recognized as difficult to compare directly due to methodological differences in evaluation, comparative analysis provides a useful benchmark for the resulting performance measures (Table 3). The false alarm forecast in Table 3 is given for the road network in Salt Lake City.

Table 3 – Results of the analysis of algorithms in [45].

| *Algorithm name* | *DR (%)* | *TTD (min)* | *FAR (%)* | *Place of use* | *SLCa forecast of network false alarms per hour* |
|---|---|---|---|---|---|
| *APID* | *86* | *2.50* | *0.05%* | *Toronto, Boston* | *7.74* |
| *DES* | *92* | *0.70* | *1.87%* | *Toronto* | *289.48* |
| *ARIMA* | *100* | *0.40* | *1.50%* | *Laboratory* | *232.20* |
| *Bayesian* | *100* | *3.90* | *0%* | *Laboratory* | *0.00* |
| *California* | *82* | *0.85* | *1.73%* | *California, Chicago, Texas* | *267.80* |

| | | | | | |
|---|---|---|---|---|---|
| *Low-Pass Filter* | *80* | *4.00* | *0.30%* | *Laboratory* | *46.44* |
| *McMaster* | *68* | *2.20* | *0.0018%* | *Minnesota* | *0.28* |
| *Neural network* | *89* | *0.96* | *0.012%* | *Laboratory* | *1.86* |
| *SND* | *92* | *1.10* | *1.30%* | *Not Known* | *201.24* |
| *SSID* | *100* | *-* | *0.20%* | *Laboratory* | *30.96* |
| *California No. 7* | *67* | *2.91* | *0.134%* | *California, Chicago, Texas* | *20.74* |
| *California No. 8* | *68* | *3.04* | *0.177%* | *California, Chicago, Texas* | *27.40* |
| *Video analysis* | *90* | *0.37* | *3.00%* | *France* | *0.03* |
| *Cell phone usage* | *100* | *-* | *5.00%* | *n/a* | *0.005* |

In the study [35], a fuzzy logic-based incident detection algorithm was proposed and compared with algorithms such as California TSC#7, APID, PATREG, SND, Bayesian, and the McMaster algorithm. The algorithm's performance was evaluated using data from the research [7]. The results showed the following effectiveness for the fuzzy logic-based algorithm: DR – 100%; FAR – 3.33%; MTTD - 0.68 min.

In the research [44], a comparative analysis of incident detection algorithms based on Artificial Neural Networks (ANN) and Probabilistic Neural Networks (PNN), along with classical algorithms (California, McMaster, etc.), was presented. The summarized results in Table 4 indicated relatively high levels of efficiency, especially for ANN and PNN. This suggests significant value for traffic monitoring systems during deployment [51-60].

Table 4 - Comparative analysis of algorithms conducted in Australia [44]

| *Algorithm name* | *DR, %* | *FAR, %* | *MTTD, min.* |
|---|---|---|---|
| *McMaster* | *68-88* | *<0.01* | *2.1-3.2* |

| | | | |
|---|---|---|---|
| *DELOS [37]* | *78* | *0.176* | *1.1* |
| *ANN [53]* | *89* | *0* | *2.4* |
| *ANN [53]* | *89* | *0* | *2.4* |
| *ANN [40]* | *83* | *0.065* | *3.4* |
| *PNN [1]* | *98-100* | *0-0.5* | *0.3-2.5* |
| *California 8 Algorithm [38]* | *71* | *0.005* | *8.9* |
| *DELOS [38]* | *73* | *0.03* | *5.5* |
| *ANN [38]* | *97* | *0.176* | *5.2* |
| *PNN [60]* | *93* | *0.057* | *2.7* |
| *ANN [60]* | *83* | *0.065* | *3.4* |

The authors proposed a method of responding to traffic flow using an incident detection algorithm in their publication [50]. The proposed method involves online calibration of threshold values for the California No. 7 and DELOS algorithms, which makes them more robust to changing traffic flow conditions. During testing in Athens, Greece, the proposed algorithm demonstrated a 20% increase in DR efficiency and a 25% reduction in FAR when compared to existing algorithms.

## Conclusion

The analysis revealed numerous incident detection algorithms, which are continuously evolving and improving, particularly with the advancement of big data analysis. However, the practical application of these algorithms is restricted due to the high rate of false positives.

Therefore, the employment of fixed vehicle detectors for highways in incident detection algorithms necessitates improvement or the integration of supplementary systems for daily traffic monitoring. This will enable their use as integrated components of intelligent transport systems.

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