Dmytro Pastukh

DESIGN IN THE DEVELOPMENT OF SMART TRANSPORTATION SYSTEMS

Engineering, Technology, and Design in the Development of Smart Transportation Systems and Their Adaptation to the Classical Principles of TRIZ and ARIZ

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Over the past several years, smart technologies have progressively expanded into virtually every sector of modern society. Today, some of the most advanced application areas include Smart Manufacturing, Smart Transportation, Smart Medical Technologies (Smart MedTech), and Smart Design. Among these domains, Smart Transportation is distinguished by its exceptional diversity of technologies and engineering solutions. For this reason, it constitutes the primary focus of the present book.

Keywords: *Theory of Inventive Problem Solving (TRIZ); Algorithm for Inventive Problem Solving (ARIZ); Smart Transportation; Smart Vehicle; Optimization of Vehicle Systems and Components; Smart Transportation in Smart Cities*

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Introduce

Over the past several years, smart technologies have progressively expanded into virtually every sector of modern society. Today, some of the most advanced application areas include Smart Manufacturing, Smart Transportation, Smart Medical Technologies (Smart MedTech), and Smart Design.

Among these domains, Smart Transportation is distinguished by its exceptional diversity of technologies and engineering solutions. For this reason, it constitutes the primary focus of the present book.

The principal motivation for concentrating on Smart Transportation lies in the fact that the innovative technologies developed for intelligent transport systems are applicable far beyond the transportation sector itself. Many engineering concepts, technical solutions, and software architectures originally created for smart transport can be successfully transferred to other industrial fields that employ similar technological principles. One example is the application of homogenization technologies: while fuel homogenization is used in transportation systems to improve combustion efficiency, analogous homogenization processes are widely employed in the dairy and food industries for milk processing. Such examples illustrate the broad interdisciplinary potential of Smart Transportation technologies.

Some researchers argue that Smart Transportation is fundamentally based on mobile applications and digital communication platforms, which subsequently provide the technological foundation for Smart Cities. This perspective is valid when considering purely electric transportation systems. However, the global vehicle fleet currently consists of several hundred million vehicles, the overwhelming majority of which are powered by internal combustion or diesel engines. Consequently, the implementation of Smart Transportation systems must also address the integration of these conventional vehicles, requiring solutions to numerous technical and environmental challenges that are largely absent in fully electric transportation.

Furthermore, current electric vehicle technologies have not yet reached their full technological maturity. As the number of electric vehicles continues to increase, systematic optimization of their major systems and components – including energy storage, power electronics, electric drives, charging infrastructure, and intelligent control systems – will become increasingly important.

The continued optimization of both electric and conventional vehicles, together with the integration of heterogeneous transportation technologies into unified Smart Transportation systems, will require new approaches to generating engineering innovations. In turn, this creates the need to extend and adapt the classical principles of the Theory of Inventive Problem Solving (TRIZ) and the Algorithm for Inventive Problem Solving (ARIZ) to meet the requirements of modern intelligent transportation technologies.

The concepts presented in this book demonstrate that Smart Transportation should be regarded not merely as a transportation technology, but as a multidisciplinary engineering platform that combines mechanical engineering, electronics, information technologies, artificial intelligence, communication systems, environmental engineering, and systematic innovation methodologies to support the development of future intelligent mobility systems.

Figure 1. Conceptual front-end design of a smart vehicle intended for operation within Smart Transportation systems. The design incorporates an underfloor battery compartment and dedicated air-cooling channels for battery thermal management during vehicle operation. The extensive glazing maximizes optical visibility, facilitating remote vehicle supervision as well as autonomous driving functions

Experience accumulated over the past several years demonstrates that smart technologies are steadily expanding into virtually every area of modern society. Among the most mature application domains are Smart Manufacturing, Smart Transportation, Smart Medical Technologies (Smart MedTech), and Smart Design.

Among these, Smart Transportation represents one of the most technologically diverse and rapidly evolving fields. For this reason, it is the principal subject of the present book.

The primary reason for focusing on Smart Transportation is that many technological innovations developed for intelligent transportation systems can be transferred to numerous other engineering disciplines. The underlying technical architectures, software solutions, and engineering principles frequently have direct analogues in other industries. For example, fuel homogenization technologies developed for transportation applications share common physical principles with homogenization processes employed in the dairy and food industries for milk processing. Such similarities demonstrate the interdisciplinary nature of engineering innovation and the broad applicability of technologies originally developed for intelligent transportation systems.

Some researchers argue that Smart Transportation is primarily based on mobile applications and digital communication platforms that ultimately serve as the technological foundation for Smart Cities. This statement is largely valid when considering purely electric transportation systems. However, the worldwide vehicle fleet currently consists of several hundred million vehicles, most of which continue to rely on internal combustion and diesel engines. Consequently, the implementation of comprehensive Smart Transportation systems must also include conventional vehicles. Their integration requires solutions to numerous engineering, environmental, and operational challenges that are either significantly less pronounced or absent in fully electric transportation.

Moreover, present-day electric vehicle technology is still undergoing rapid development. As the number of electrically powered vehicles continues to grow, systematic optimization of their principal systems and components – including battery technologies, thermal management systems, electric drives, power electronics, intelligent control units, and charging infrastructure – will become increasingly important.

The continued optimization of electric vehicles together with the integration of conventional vehicles into Smart Transportation networks will inevitably require new methodologies for generating engineering innovations. Consequently, there is a need to further develop and structurally adapt the classical principles of the Theory of Inventive Problem Solving (TRIZ) and the Algorithm for Inventive Problem Solving (ARIZ) to address the challenges posed by intelligent transportation technologies.

An important question therefore arises: How is Smart Transportation envisioned today, and what will vehicles look like within the intelligent transportation systems of future Smart Cities?

During the past decade, autonomous vehicles and robotic transportation technologies have made remarkable progress and continue to evolve at an accelerating pace. Major automotive manufacturers are actively developing intelligent vehicle platforms while transforming their production systems toward highly connected vehicles capable of operating within fifth-generation (5G) communication networks and future high-speed digital infrastructures.

According to many industry experts, the automotive sector will undergo fundamental transformation within the next five to seven years. As intelligent transportation infrastructure continues to develop, fully autonomous and highly automated vehicles are expected to become an integral component of future Smart Cities, where they will operate as interconnected elements of a unified cyber-physical transportation ecosystem. Current pilot programs and large-scale field trials conducted in several countries already demonstrate the practical feasibility of this technological transition.

Figure 2. Conceptual rear view of a smart vehicle designed for operation within Smart Transportation systems. The vehicle features a streamlined design that accommodates an underfloor battery pack together with dedicated air-cooling systems for thermal management during operation. The extensive glazing, particularly the panoramic roof, provides maximum optical visibility, thereby facilitating remote vehicle supervision and supporting fully autonomous driving capabilities

Roadmaps for Smart Transportation

The widespread deployment of Smart Transportation technologies will inevitably require extensive preparatory work before their large-scale implementation becomes feasible. This includes the development of new legislative frameworks governing intelligent traffic systems, as well as comprehensive modernization of transportation infrastructure.

Experience gained in many countries has demonstrated that the rapid introduction of new forms of intelligent mobility, such as electric bicycles and other micro-mobility solutions, has been accompanied by an increase in traffic accidents. These experiences clearly indicate the necessity of carefully adapting Smart Transportation technologies to real operating environments and existing transportation ecosystems.

One of the fundamental requirements for intelligent transportation systems is the ability to determine the precise geographical position of every vehicle in real time. The required positioning accuracy substantially exceeds the capabilities of conventional GPS navigation systems. Consequently, a new generation of digital road maps must be developed, many of which will represent fully three-dimensional models of transportation infrastructure.

Development of such mapping systems is already underway within the research divisions of major automotive manufacturers and technology companies. These organizations are collecting and processing enormous volumes of spatial data while constructing highly detailed virtual three-dimensional road networks.

One of the most promising approaches is the creation of **high-definition (HD) digital maps** containing lane-level road markings, traffic infrastructure, and virtual reference objects. These maps are generated using state-of-the-art high-resolution cameras, LiDAR systems, radar sensors, satellite navigation technologies, and other advanced surveying equipment.

The resulting datasets enable the construction of highly accurate three-dimensional models of highways and urban road networks, including roadside infrastructure, traffic signs, road markings, barriers, intersections, and numerous additional environmental features required for autonomous navigation.

For maps intended to support autonomous and highly automated vehicles, the highest possible level of spatial detail is essential. Equally important is the continuous updating of map information in order to reflect changes in road conditions, traffic organization, and infrastructure.

The onboard computer of an intelligent vehicle cannot operate safely without reliable digital maps, since many driving decisions are based directly on the information they provide. Continuous updating of these maps therefore requires high-speed communication networks capable of delivering real-time information to vehicles.

Furthermore, information regarding road maintenance, temporary lane closures, construction zones, accidents, or other traffic restrictions should be transmitted to vehicles well before they reach the affected area. For this reason, local transportation authorities and infrastructure operators must actively participate in the collection, verification, and distribution of current road information, thereby ensuring the safe and efficient operation of future Smart Transportation systems.

Concept of Future Smart Vehicles

Internet Connectivity

With the continued development of the **Internet of Things (IoT)** and the emergence of **Smart Cities**, future vehicles will become permanently connected to the Internet. Continuous connectivity will support real-time updating of digital road maps, traffic monitoring, route optimization, and interaction with intelligent transportation infrastructure.

Internet connectivity will also enable personal mobile devices to communicate seamlessly with vehicle information systems. Intelligent voice assistants will become an integral part of vehicle operation, allowing drivers and passengers to control navigation, vehicle functions, and information services using natural language commands. Upon receiving a spoken request, the onboard intelligent system will automatically determine the optimal route and provide additional information relevant to the journey.

Wireless communication technologies will further enable remote vehicle management through smartphone applications, which are expected to replace conventional electronic key fobs. Such applications will provide significantly broader functionality than simple door locking and unlocking. They will allow owners to monitor fuel level or battery state of charge, tire pressure, vehicle mileage, component wear, maintenance schedules, diagnostic information, and numerous other operating parameters in real time.

Continuous network connectivity of smart vehicles will also provide substantial benefits for municipal authorities. The collection and intelligent analysis of transportation data generated by connected vehicles will create new opportunities for traffic management, infrastructure optimization, environmental monitoring, and urban mobility planning, ultimately contributing to more efficient Smart City transportation systems.

Shared Mobility and Autonomous Ride-Sharing

Shared mobility services, in which several passengers traveling in similar directions share the cost of a private vehicle, are expected to become an integral component of future Smart Transportation systems.

This concept has already gained widespread popularity owing to the availability of mobile communication technologies. Through online applications, users can identify other travelers with similar destinations, whether commuting to work or undertaking longer journeys, thereby reducing transportation costs while improving travel convenience. Such services also contribute to reduced traffic congestion and lower demand for public transportation during peak periods.

Many transportation experts consider **autonomous shared vehicles** to represent one of the most promising directions in the evolution of urban mobility. With the deployment of intelligent autonomous vehicles, organizing shared transportation services will become considerably simpler and more efficient.

For example, after a passenger requests an autonomous taxi, the intelligent transportation management system may dynamically assign additional passengers whose destinations are compatible with the planned route. As a result, the autonomous vehicle can transport multiple passengers simultaneously while minimizing travel time and maximizing vehicle utilization.

Technological Foundations of Future Vehicles

The realization of future intelligent vehicles requires significant advances in several technological fields, including high-performance software, artificial intelligence, computer vision, advanced sensor technologies, autonomous navigation systems, high-speed communications, and intelligent decision-support algorithms.

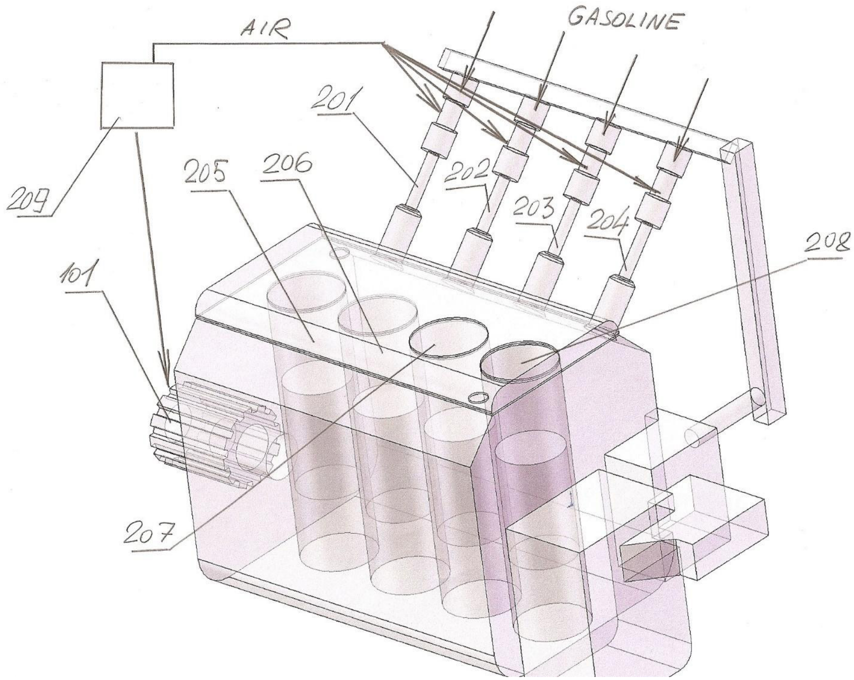

Figure 3. Conceptual model for optimization of the fuel supply system and the internal combustion engine of a smart vehicle operating within Smart Transportation systems in a Smart City

For autonomous mobility services to achieve widespread public acceptance, they must offer greater comfort, higher efficiency, improved safety, and lower operating costs than conventional privately owned vehicles.

Furthermore, autonomous driving technologies are expected to play a major role in reducing road traffic accidents, decreasing fatalities and injuries, improving transportation safety, and enhancing the overall efficiency and sustainability of future Smart Transportation systems.

The figure illustrates one possible approach to improving engine performance and reducing environmental impact through **online homogeneous mixing of gasoline with compressed air prior to combustion**.

Reference numerals:

101 – engine output shaft;

201 – online gasoline–compressed air mixing device;

202 – online gasoline–compressed air mixing device;

203 – online gasoline–compressed air mixing device;

204 – online gasoline–compressed air mixing device;

205 – first engine cylinder;

206 – second engine cylinder;

207 – third engine cylinder;

208 – fourth engine cylinder;

209 – miniature compressor driven by the engine output shaft.

A significant advantage of this approach is that modifications of this type can be implemented on virtually any conventional internal combustion or diesel engine. This makes it possible to continue operating existing vehicle fleets within future Smart Transportation systems, particularly during the transitional stages preceding complete electrification.

Smart Transportation of the Future

Helsinki is one of the participating cities in an international initiative aimed at advancing next-generation public transportation through the integration of autonomous vehicles into everyday urban mobility.

In addition to Helsinki, the project involves London, Paris, Austin (Texas), Los Angeles, Washington, Nashville, São Paulo, Buenos Aires, and Tel Aviv. The initiative brings together experts from multiple engineering and scientific disciplines to jointly develop recommendations, methodologies, and practical tools for implementing intelligent transportation systems.

One of Helsinki's principal advantages is its extensive use of open data, which provides an effective foundation for advanced mobile applications. These applications enable real-time monitoring of public transportation services, traffic conditions, and urban mobility, thereby significantly improving the efficiency of intelligent transportation management.

Returning to the engineering aspects of Smart Transportation, particular attention should be devoted to the development of optimized vehicle designs and technical solutions for upgrading conventional internal combustion and diesel engines. Such modifications are intended to improve their operational efficiency, reduce environmental impact, and ensure their compatibility with the functional requirements of future Smart Transportation systems operating within Smart Cities.

These engineering solutions are expected to facilitate a gradual transition from conventional propulsion technologies to fully intelligent transportation systems while maintaining compatibility with existing vehicle fleets and transportation infrastructure.

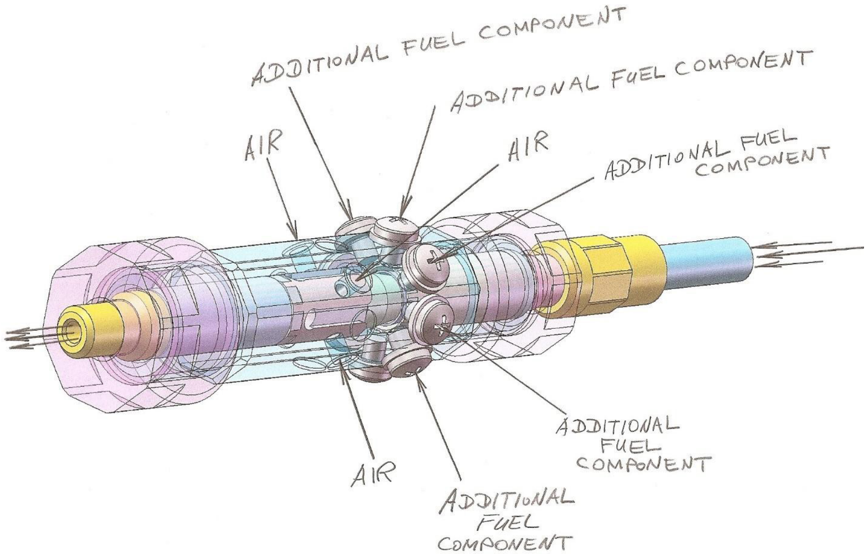

Figure 4. Conceptual design of a fuel activation device having technical characteristics and operating parameters consistent with those expected for future Smart Vehicles intended for operation within Smart City transportation systems

The proposed device performs several complementary functions, enabling it to operate with equal efficiency both in the **homogeneous mixing of liquid fuel with compressed air** and in the **homogeneous blending of multiple liquid fuel components**. Following this process, the resulting mixture may be further combined with either compressed air or water to produce stable emulsions.

Depending on the intended application, the device is capable of generating both water-in-oil (W/O) and oil-in-water (O/W) emulsions.

As illustrated in the figure, the proposed design combines compact overall dimensions with high processing capacity, making it suitable for integration into modern automotive fuel systems.

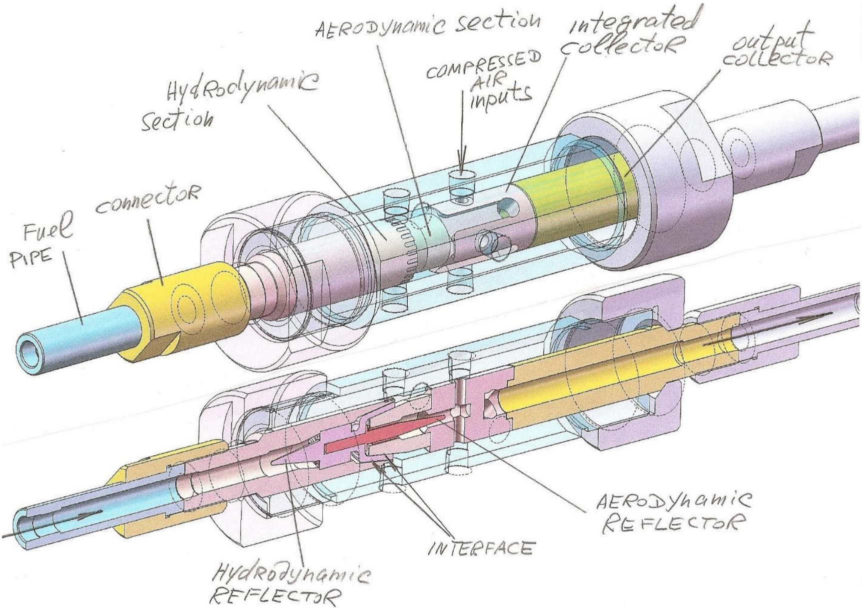

Figure 5. The figure presents the device as a transparent three-dimensional model together with its longitudinal sectional view. As illustrated, despite the multiple functions performed by the device, it contains no moving components. The design follows the principle of a calibrated outer housing, within which all internal elements are concentrically aligned along the central bore. Collectively, these elements form a system of activating flow channels responsible for the operating characteristics of the device

One of the principal engineering advantages of the device is the complete absence of moving mechanical components. Owing to the optimized internal flow geometry, the flowing fuel encounters virtually no significant hydraulic resistance. Consequently, the pressure loss between the inlet and outlet of the device does not normally exceed **10%**. Furthermore, by optimizing the dimensions of the internal flow passages and working clearances, the pressure drop can be reduced to approximately **3–5%**.

Installation of the device is straightforward and does not require specialized equipment or complex installation procedures. Its compact construction allows integration into existing fuel systems with minimal modifications, making it suitable both for newly manufactured vehicles and for retrofitting conventional internal combustion and diesel engines intended for operation within future Smart Transportation systems.

The proposed internal configuration provides several important engineering advantages:

- **Elimination of hydraulic resistance zones**, resulting in a pressure loss between the inlet and outlet that generally does not exceed **10%**;
- **Formation of a reduced-pressure region within the coaxial flow channel**, which promotes homogenization of turbulence intensity across the entire cross-section of the flowing medium;
- **Capability of homogeneously mixing multiple liquid and gaseous components** directly within the flowing stream while maintaining a high degree of mixture uniformity.

Innovation and the Theory of Inventive Problem Solving

Having considered the engineering aspects of the proposed device, attention can now be directed toward its innovative significance and its relationship to the Theory of Inventive Problem Solving (TRIZ).

Consider the problem of developing innovative solutions for Smart Transportation systems from the perspective of a technology start-up.

At the initial stage of its development, a typical start-up operates under severe resource constraints. These limitations extend not only to financial resources but also to professional expertise, engineering capabilities, technical infrastructure, manufacturing facilities, and organizational capacity.

An important question therefore arises: Can a newly established company systematically improve its ability to generate inventions? More specifically, is it possible to incorporate the accumulated inventive experience of previous generations working within related technological domains while operating under similarly limited initial conditions? If so, what constitutes this accumulated knowledge?

A related question concerns the relative contributions of structured inventive methodology and innate creative ability. To what extent does successful invention depend on systematic engineering techniques that can be learned and mastered, and to what extent does it rely upon natural creative talent?

The Soviet engineer, inventor, patent specialist, and scientist Genrich Altshuller, the founder of TRIZ, firmly believed that successful inventions exhibit recurring patterns that can be identified, formalized, and taught. To verify this hypothesis, more than 40,000 inventor's certificates and patents were systematically analyzed. Based on the observed regularities governing the evolution of technical systems and inventive solutions, the Theory of Inventive Problem Solving (TRIZ) was developed.

Today, however, both engineering challenges and the methods required to solve them differ substantially from those encountered during the early development of TRIZ. Modern engineering systems increasingly incorporate advanced composite materials, mobile applications, programmable controllers, embedded processors equipped with artificial intelligence capabilities, and numerous intelligent hardware and software technologies.

These emerging technologies establish entirely new relationships among system components and make it possible to introduce innovative technical and technological interactions into conventional engineering systems. They also require close integration between physical engineering solutions and software-based functionality. Although software alone is generally not regarded as a technical solution and therefore cannot normally be patented as an invention, software has nevertheless become an indispensable component of virtually every modern intelligent engineering system.

When an inventor encounters a technical problem for the first time – particularly during the early stages of a project – the problem is usually formulated in broad and ambiguous terms, providing little guidance toward an effective solution. Moreover, newly established companies rarely possess production facilities or experimental equipment that would allow extensive prototyping and testing.

Within the framework of TRIZ, this initial state of uncertainty is referred to as an inventive situation. Its principal disadvantage lies in the enormous number of possible solution paths available to the engineer. Evaluating all alternatives is both time-consuming and costly, while selecting directions at random inevitably leads to the inefficient trial-and-error approach.

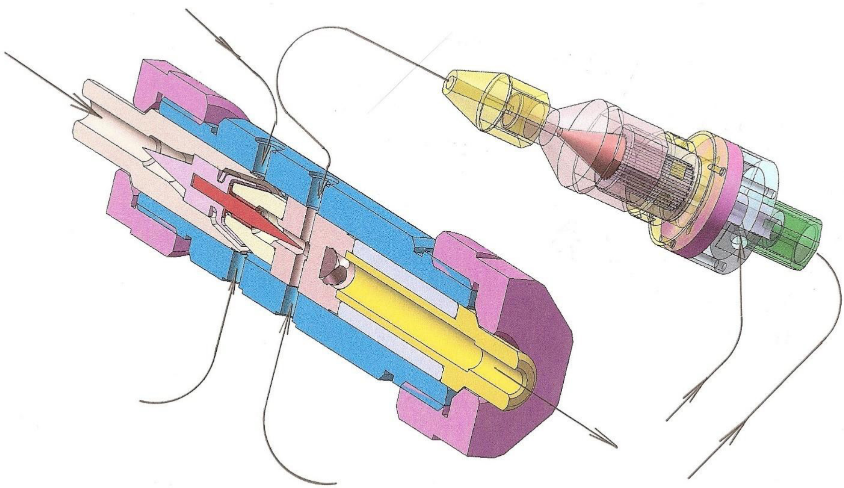

Figure 6. The figure illustrates an engineering solution in which the unique operating characteristics of the proposed device, together with additional devices of similar design, are used to implement an online sequential fuel-mixing system for a Smart Vehicle. Within this configuration, a finely dispersed aerosol is generated in parallel with the main fuel flow and subsequently mixed with the primary fuel stream, thereby improving mixture homogeneity and combustion efficiency

Consequently, the first step toward an effective invention is to reformulate the initial inventive situation into a precisely defined engineering problem in such a way that unpromising solution paths are eliminated from consideration. This immediately raises a fundamental question: Which engineering solutions should be regarded as effective, and according to what objective criteria can ineffective solutions be distinguished?

This question forms the conceptual foundation of both the classical TRIZ methodology and its adaptation to the development of modern Smart Transportation systems.

Genrich Altshuller proposed that the most effective solution to an engineering problem is one that is achieved by utilizing the resources already available within the system, without introducing unnecessary complexity or additional components.

This concept led him to formulate one of the central principles of TRIZ – the Ideal Final Result (IFR). According to this principle, an engineering system should evolve toward a state in which *a certain element of the system or its surrounding environment (the so-called X-element) independently eliminates the undesirable effect while preserving or even enhancing the useful function of the system.*

In practical engineering, a completely ideal solution is rarely attainable. Nevertheless, the Ideal Final Result serves as a strategic guideline for inventive thinking. The closer a technical solution approaches the IFR, the more effective, elegant, and resource-efficient it is considered to be.

The engineering solution presented in Figure 6 represents an example of a design concept that approaches the Ideal Final Result. By exploiting the intrinsic hydrodynamic and aerodynamic characteristics of the device, the required fuel activation and homogenization processes are achieved without the use of mechanically driven mixing components. As a result, the system maintains a simple and compact construction while simultaneously improving fuel preparation, combustion quality, engine efficiency, and environmental performance.

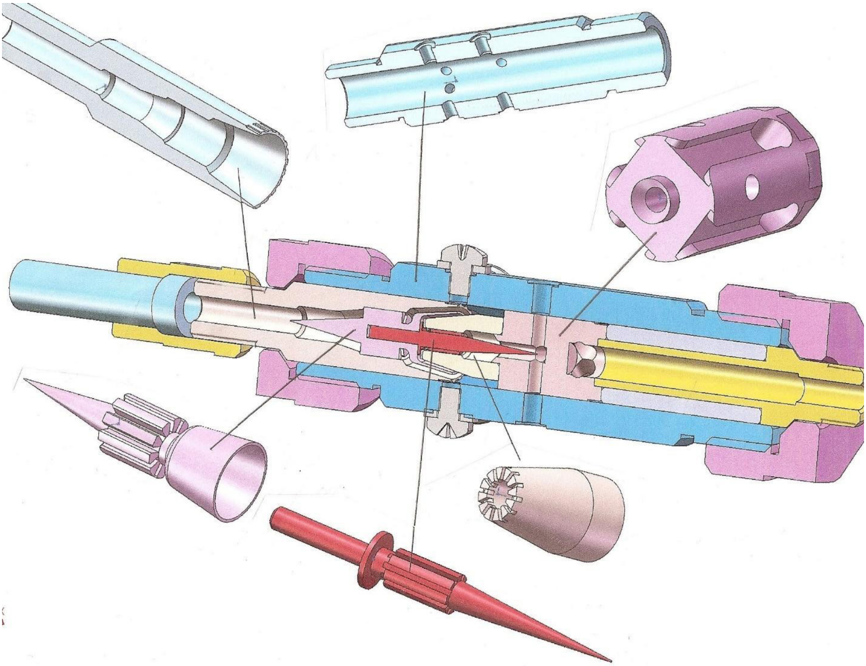

Figure 7. The figure illustrates a device whose design closely approaches the Ideal Final Result (IFR) according to the principles of three-dimensional engineering design and integrated computer modeling. All structural components are developed within a unified engineering and industrial design concept. The proposed configuration combines high manufacturing accuracy with a simple structural layout and exceptional mechanical reliability. Furthermore, every component of the device can be manufactured using computer numerical control (CNC) machining, while the outer housing simultaneously serves as a precision reference element that accurately aligns all internal components along the central axis

The authors present this solution as an example of engineering development guided by the principles of TRIZ, demonstrating how the systematic use of existing physical resources can lead to highly efficient technical solutions for future Smart Transportation systems.

The proposed concept also achieves high dimensional accuracy without the use of moving mechanical parts, thereby minimizing manufacturing complexity, assembly costs, and maintenance requirements.

Another important advantage of this design is its high degree of universality. As a result, both the device and the technology it implements can be applied to a wide variety of internal combustion and hybrid propulsion systems, including those intended for integration into future Smart Transportation platforms.

Having obtained a methodological tool for eliminating inefficient engineering solutions, the original inventive situation can be reformulated into the standard TRIZ mini-problem.

According to the concept of the Ideal Final Result (IFR), the system should remain essentially unchanged while either the undesirable property disappears or a new beneficial property is introduced without creating additional complexity.

The fundamental purpose of the mini-problem is to avoid expensive and extensive redesign while directing attention toward the simplest, most resource-efficient engineering solutions.

Formulating the mini-problem enables the engineer to define the problem more precisely by addressing several fundamental questions:

- What are the principal components of the system, and how do they interact?

- Which interactions are harmful, which are neutral, and which contribute positively to system performance?
- Which components and relationships may be modified, and which must remain unchanged?
- Which modifications improve overall system performance, and which introduce new disadvantages?

At first glance, these questions appear sufficient to initiate the inventive process. However, during the early stages of developing a technological start-up, the engineering objective extends far beyond the creation of an invention itself. The ultimate goal is the development of a commercially successful product.

An equally important question therefore arises: How can the most valuable technical characteristics of a future invention be transformed into a set of consumer-oriented properties capable of ensuring not only technological excellence but also commercial competitiveness?

To answer this question, the engineering design process should be modeled step by step.

Once the mini-problem has been formulated and the engineering system has been analyzed, it quickly becomes evident that attempts to improve one group of system parameters frequently lead to deterioration of others. This phenomenon is one of the central concepts addressed by the TRIZ methodology.

As demonstrated by the previous examples, the proposed engineering design philosophy enables extensive multifunctional computer modeling and numerical simulation already during the conceptual design stage. This approach makes it possible to evaluate alternative engineering solutions and estimate their proximity to the Ideal Final Result before prototype manufacturing begins.

Furthermore, if virtual engineering simulations are supplemented by computational evaluation of different structural materials and advanced composites, it becomes possible to predict the technical characteristics of the future system while maintaining identical external geometry.

Consequently, the same geometric configuration can be engineered to exhibit different predefined performance characteristics. For example, depending on the selected materials and structural configuration, the system may provide controlled heating of the fuel flow or operate without thermal conditioning while preserving identical external dimensions.

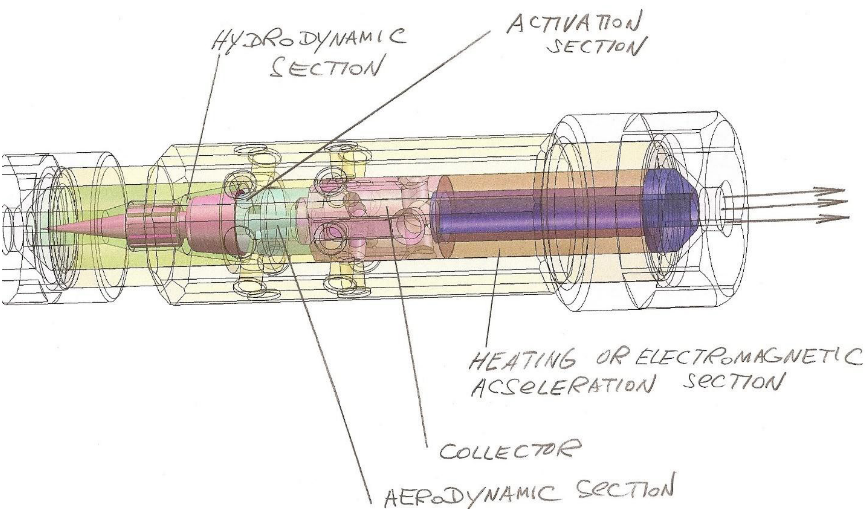

Figure 8. Illustrates such a design concept, demonstrating a device that maintains unchanged external dimensions while providing different output characteristics through optimized internal engineering solutions and material selection

For comparison, it should be noted that the application of conventional engineering design approaches frequently leads to the emergence of various types of contradictions.

For example, increasing the structural strength of an aircraft wing generally results in an increase in its weight, whereas reducing its weight often decreases its mechanical strength. Consequently, the engineering system develops a conflict, or **contradiction**, between competing design objectives.

According to the **Theory of Inventive Problem Solving (TRIZ)**, contradictions are classified into three principal categories, arranged in order of increasing complexity of resolution.

Administrative Contradiction

An **administrative contradiction** may be expressed as follows:

"The system must be improved, but I do not know how to accomplish this, or I do not possess the authority, resources, or expertise required to implement the solution."

This represents the least complex type of contradiction and can often be resolved through additional knowledge acquisition, organizational changes, or appropriate managerial decisions.

In the contemporary innovation environment, however, many administrative contradictions arise not only from organizational limitations but also from **commercial constraints** associated with the future commercialization of an invention and its transformation into a competitive technological product. Consequently, market requirements increasingly become an integral component of the engineering decision-making process.

Technical Contradiction

A technical contradiction occurs when improving one parameter of an engineering system inevitably causes deterioration of another parameter.

This type of contradiction constitutes the classical formulation of an inventive engineering problem. Reformulating an administrative contradiction as a technical contradiction significantly reduces the complexity of the problem, narrows the search space, and enables the engineer to replace inefficient trial-and-error approaches with the systematic methodology provided by TRIZ and the Algorithm for Inventive Problem Solving (ARIZ).

Depending on the complexity of the problem, the methodology recommends either the application of one or more standard inventive principles or the identification of the underlying physical contradiction requiring resolution.

Under present-day conditions, technical contradictions should also be evaluated in conjunction with the commercial requirements of future products. Modern engineering solutions must simultaneously satisfy technical performance objectives, manufacturing constraints, environmental regulations, production costs, reliability requirements, and market competitiveness.

Physical Contradiction

A physical contradiction represents the most fundamental category of engineering contradiction.

It arises when a particular component of a system must simultaneously possess mutually exclusive physical properties in order to achieve the desired system performance. Since such conditions violate the fundamental laws of physics, resolving physical contradictions requires the application of appropriate physical effects and scientific principles.

Traditionally, engineers addressed such problems using reference databases of physical effects together with the classical inventive principles developed within the TRIZ methodology.

What Has Changed?

The engineering environment in which TRIZ was originally developed has changed dramatically.

The emergence of advanced computer-aided engineering (CAE) technologies, computer-aided design (CAD) systems, digital simulation platforms, numerical optimization methods, digital twins, artificial intelligence, and engineering software environments has substantially expanded the set of tools available for inventive problem solving.

Today, engineers are able to evaluate thousands of alternative design solutions virtually before manufacturing a physical prototype. Three-dimensional modeling, finite-element analysis, computational fluid dynamics, multiphysics simulation, optimization algorithms, and AI-assisted engineering enable contradictions to be identified and resolved during the earliest stages of product development.

As a result, modern engineering design no longer relies solely on the classical TRIZ methodology. Instead, TRIZ increasingly functions as a conceptual framework that is complemented by advanced digital engineering technologies capable of rapidly validating alternative solutions and identifying those that most closely approach the Ideal Final Result (IFR).

This integration of classical inventive methodologies with digital engineering tools represents one of the defining characteristics of the development of future Smart Transportation systems and other intelligent technological platforms.

Figure 9. The figure presents the individual components of the proposed device. Throughout every stage of engineering design and manufacturing, particular emphasis has been placed on preventing the emergence of engineering contradictions while preserving the highest possible level of functional efficiency

System of Inventive Principles

The analysis of many thousands of inventions has demonstrated that, despite the enormous diversity of engineering problems, the majority of technical contradictions can be resolved through the application of forty fundamental inventive principles.

The development of this system of inventive principles was initiated by Genrich S. Altshuller during the early stages of the development of the Theory of Inventive Problem Solving

(TRIZ). Their identification required the systematic analysis of more than 40,000 inventor's certificates and patents, allowing recurring patterns in successful engineering solutions to be identified and formalized.

These inventive principles continue to possess considerable heuristic value for engineers and inventors. Knowledge of these principles significantly facilitates the search for effective engineering solutions by directing attention toward promising areas of innovation and reducing reliance on inefficient trial-and-error approaches. However, in today's technological and commercial environment, the classical system of inventive principles is no longer sufficient by itself for developing successful innovation-driven products.

It is important to recognize that the inventive principles merely indicate the direction in which potentially effective solutions may be found. They do not generate a complete engineering solution or specify the optimal design. The creative process of transforming these general principles into a practical technical implementation remains the responsibility of the engineer.

In modern engineering practice, this process is increasingly supported by advanced digital technologies, including computer-aided design (CAD), computer-aided engineering (CAE), numerical optimization, digital simulation, artificial intelligence, and digital twin technologies. Together with the classical TRIZ methodology, these tools enable engineers not only to identify promising directions for innovation but also to evaluate, optimize, and validate alternative solutions before physical prototypes are manufactured.

Consequently, contemporary engineering design may be viewed as the integration of systematic inventive methodologies with digital engineering technologies, thereby combining structured creative thinking with high-performance computational analysis. This integrated approach is particularly important for the development of future Smart Transportation systems, where engineering decisions must simultaneously satisfy technical, environmental, economic, manufacturing, and commercial requirements.

Figure 10. The figure illustrates a device developed in accordance with the principles, methodologies, and inventive techniques of the Theory of Inventive Problem Solving (TRIZ), adapted to meet the emerging engineering requirements associated with the development of Smart Transportation infrastructure and its constituent systems. Despite its compact dimensions, the device demonstrates high operational performance, being capable of processing up to 100 liters of fuel mixture per hour while maintaining a high degree of homogeneity, including a highly uniform turbulence distribution throughout the flowing mixture

During the development of the device, the recommendations of both the basic and paired inventive principles aimed at achieving the Ideal Final Result (IFR) were taken into account.

These principles were appropriately adapted to satisfy the engineering requirements of intelligent transportation systems, smart vehicles, intelligent propulsion systems, and advanced fuel management technologies.

The system of inventive principles employed within TRIZ comprises both individual inventive principles and their complementary paired counterparts. In modern engineering practice, these principles are increasingly integrated with digital software technologies that support every stage of product development, including conceptual design, engineering analysis, manufacturing, testing, and operational monitoring.

Individual inventive principles are primarily intended to resolve technical contradictions. Among these, the classical set of forty inventive principles remains the most widely recognized and extensively applied methodology for systematic innovation.

Paired inventive principles combine a classical inventive principle with a complementary integrative principle, thereby extending the methodology to the resolution of more complex physical contradictions. Such contradictions frequently require the simultaneous consideration of multiple opposing actions, physical states, material properties, or combinations of conventional and advanced composite materials. This expanded methodology significantly increases the range of engineering solutions available for modern intelligent systems.

An important component of TRIZ is the system of Standards for Inventive Problem Solving, which represents an organized collection of solution models employing physical, chemical, geometrical, and other scientific effects for eliminating engineering contradictions. These standards may be regarded as generalized engineering templates that not only facilitate the solution of existing technical problems but also assist in identifying new engineering challenges that arise as innovative technological elements are incorporated into existing systems. In the era of digital engineering, these technological elements increasingly include artificial intelligence, programmable control systems, digital communication technologies, and cyber-physical infrastructures.

To describe the structure of such engineering solutions, Genrich Altshuller introduced the concept of Substance–Field (Su-Field) Analysis, which models the interaction between material objects and physical fields within a minimal technical system. In the context of Smart Manufacturing and Smart Transportation, this classical model can be expanded to include the influence of digital technologies, resulting in a more comprehensive analytical framework that may be represented as Hardware + Substance + Field + Software + Method. Such an extended representation more accurately reflects the architecture of contemporary intelligent engineering systems.

Today, computer-based engineering has become the fundamental component of Substance–Field Analysis. Advanced computer-aided design (CAD), computer-aided engineering (CAE), digital twins, numerical simulation, and artificial intelligence are now closely integrated into the engineering design process, enabling comprehensive virtual simulation of physical processes long before prototype manufacturing begins.

The TRIZ system of standards is organized into classes, subclasses, and individual solution standards, comprising a total of 76 standard solutions. Besides facilitating the resolution of engineering contradictions, this structured methodology enables engineers to identify previously unrecognized technical problems, predict the future evolution of engineering systems, and evaluate alternative technological development pathways.

Substance–Field Analysis itself is based upon the interaction between substances and fields, providing a generalized representation of the minimum functional engineering system. Within Smart Manufacturing and Smart Transportation environments, however, software increasingly becomes an essential engineering resource. Consequently, contemporary analysis extends beyond the traditional *Substance + Field* model to incorporate computational intelligence and digital control, thereby establishing a unified framework that integrates physical hardware, engineering materials, physical fields, software, and operational methodologies.

Genrich Altshuller also developed systematic methods for analyzing engineering resources available within a technical system. Several TRIZ principles specifically address the identification and utilization of existing substances, physical fields, and other available resources for resolving engineering contradictions while increasing the degree of system ideality.

A classical example is the teletext system, which utilizes unused intervals within conventional television broadcast signals to transmit digital information. Rather than introducing additional transmission channels, the system exploits existing resources that were previously unutilized.

A similar resource-oriented philosophy remains one of the central concepts of modern inventive engineering. Contemporary designers increasingly analyze not only the resources actively employed within a system but also latent physical, informational, computational, and material resources available either inside the engineering system itself or within its surrounding environment. The identification and effective utilization of such hidden resources frequently provide the basis for highly efficient engineering innovations.

One of the most important developments derived from the TRIZ methodology is ARIZ (Algorithm for Inventive Problem Solving), which provides a structured procedure for transforming an ill-defined inventive situation into a sequence of logically connected engineering steps leading toward the systematic resolution of complex technical and physical contradictions. In contemporary engineering practice, ARIZ is increasingly complemented by digital simulation, computational optimization, artificial intelligence, and advanced engineering software, significantly extending its capabilities in the design of future Smart Transportation systems.

Algorithm for Inventive Problem Solving (ARIZ)

The Algorithm for Inventive Problem Solving (ARIZ) is a structured, step-by-step methodology for identifying and resolving engineering contradictions, thereby providing a systematic approach to solving inventive problems. In its classical form, ARIZ consists of approximately 85 sequential steps, guiding the engineer from an initially ill-defined inventive situation to a technically justified solution.

ARIZ comprises three principal components: the algorithm itself, an information support system based on accumulated engineering knowledge and information resources, and methods for managing psychological factors that influence creative thinking. The latter are closely related to techniques for the Development of Creative Imagination (DCI), which are intended to stimulate innovative thinking and enhance the inventor's ability to generate unconventional engineering solutions.

A variety of alternative methodologies have also been developed to assist inventors in realizing their creative potential. Most of these approaches are heuristic in nature and are based primarily on principles of psychology and logical reasoning. Unlike TRIZ, however, they do not claim the status of a comprehensive scientific theory of inventive problem solving.

Among the best-known heuristic methods are the Trial-and-Error Method, Brainstorming, Morphological Analysis, the Method of Focal Objects, and the Checklist (Control Questions) Method. Although these techniques remain useful for idea generation, they generally lack the systematic analytical framework characteristic of TRIZ.

Modern TRIZ

Contemporary TRIZ has evolved into several independent schools that continue developing the classical methodology while introducing new concepts and application areas that were absent from the original theory.

At the same time, the fundamental technical core of classical TRIZ – including the Forty Inventive Principles, ARIZ, and Substance–Field (Su-Field) Analysis – has remained largely unchanged. Most modern developments therefore focus on reinterpretation, restructuring, adaptation, and dissemination of TRIZ rather than on fundamental modification of its engineering foundations. Consequently, many contemporary TRIZ schools emphasize philosophical, educational, and methodological aspects to a greater extent than purely technical developments.

An important characteristic of modern TRIZ is the increasing integration of digital engineering technologies throughout every stage of product development. Computer-aided design (CAD), computer-aided engineering (CAE), digital twins, artificial intelligence, numerical optimization, and advanced simulation environments have become integral components of contemporary engineering practice and naturally complement the systematic problem-solving framework provided by TRIZ.

Another significant trend is the expansion of TRIZ beyond its original field of technical creativity. Today, TRIZ methodologies are actively applied in business innovation, marketing, advertising, education, organizational management, product development, and even early childhood education. Nevertheless, the methodology was originally developed primarily as an engineering discipline for solving technical problems.

The classical version of TRIZ may therefore be regarded as a general engineering methodology. Effective practical application in specialized industries increasingly requires domain-specific adaptations that incorporate dedicated knowledge bases, engineering standards, technological databases, and industry-specific solution models.

Several major international corporations have already developed proprietary TRIZ-based methodologies adapted to their own technological environments. In the author's opinion, a similar approach should be adopted for technology start-ups. Specifically, a mobile digital version of TRIZ should be developed, specifically designed for computer-aided engineering environments and focused on the rapid commercialization of innovative products. Such a system would integrate classical inventive methodologies with modern digital engineering tools, significantly accelerating the transition from conceptual design to market-ready technology.

At present, however, specialized versions of TRIZ intended to stimulate scientific discoveries in disciplines such as physics, chemistry, biology, and related natural sciences remain largely undeveloped.

Another important trend in technological development is the increasing importance of protecting intellectual property and securing developers' rights to innovative technologies. Consequently, industrial demand continues to grow for systematic innovation methodologies together with integrated software platforms that support engineering creativity and product development.

An alternative approach involves maintaining openness toward new methodologies that have emerged in response to the rapidly changing technological environment. Such approaches preserve the conceptual foundations of TRIZ while adapting the methodology to contemporary engineering realities, thereby maintaining its relevance as one of the leading theoretical frameworks for systematic innovation.

The horizontal and vertical integration of the engineering concepts, technologies, and inventions discussed throughout this work has enabled the formulation of the fundamental technical requirements and design specifications for an autonomous energy generation system.

Based on this integrated approach, a conceptual engineering configuration has been developed for an autonomous power system incorporating technical solutions characteristic of intelligent technological processes. The proposed concept combines technologies aimed at reducing fuel consumption in internal combustion engines, highly efficient multi-stage energy conversion with progressive amplification of output torque, and the application of planar technologies in the design of low-speed electric generators.

The proposed system is based on the principle of sequential multi-stage energy conversion, in which each conversion stage progressively increases the equivalent power characteristics of the output energy. This integrated engineering concept provides the foundation for highly efficient autonomous energy systems intended for future intelligent technological infrastructures, including Smart Transportation and Smart City applications.

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