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Design and performance analysis of automated vertical parking systems for urban environments

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Keywords: parking, car, chain, cost, city.
Abstract: The article presents the results of work on the design, calculation, and manufacturing of vertical parking systems. Vehicle movement, together with the cradles, is carried out in both vertical and horizontal directions using a chain transmission system. The structure consists of a frame, chain drive, guide rails, and a control unit that manages cradle positioning and ensures their movement to the designated entry and exit point for vehicle parking. Saving land space is a key economic factor. Vertical parking systems allow significantly more cars to be accommodated within the same area compared to traditional surface-level parking lots. In comparison with underground or multi-level reinforced concrete parking structures, automated systems based on metal frameworks can be more cost-effective. Automated parking systems require minimal staff involvement. In closed automated systems, the risk of theft, vandalism, or accidental vehicle damage is virtually eliminated, as access is restricted to vehicle owners only. Parking spaces in areas with a shortage of parking lots are the liquid assets. These spaces be profitably leased, providing passive income, or resold. The payback period for a vertical parking installation project can be approximately three years, although this value strongly depends on specific conditions. The availability of parking in a residential or office complex directly increases the property's value and overall attractiveness.

1 Introduction

Due to the global increase in vehicle fleets, the shortage of parking spaces, especially in large cities, has become a growing concern. On average, a driver in a major city spends approximately 70 hours per year searching for parking. This not only results in wasted time but also leads to unnecessary fuel consumption. As a consequence, millions of tons of toxic emissions are released into the environment. A single car in a large city can emit around 320 kg of CO_2 per year due to the search for parking alone [1-7].

Cities around the world are increasingly adopting intelligent parking systems. These systems help address issues such as traffic congestion, environmental pollution, and inefficiencies caused by the large number of cars circling for parking in dense urban areas. The autonomous parking market is projected to grow to USD 12.9 billion by 2030, with a compound annual growth rate (CAGR) of 25.2%, which clearly demonstrates the impact that intelligent parking systems will have in the next few years [2-5].

1.1 Intelligent parking systems

- **Revenue Increase:**
  The introduction of intelligent parking meters and mobile payment systems enables more accurate monitoring and efficient collection of funds from parking spaces. More effective utilization of each parking spot leads to increased revenue and reduced losses due to unpaid fines.
- **Reduction of Parking Management Costs:**
  Tracking all parking-related activities allows for significant cost savings. The collected data helps identify best practices and optimize enforcement measures, leading to more efficient operations.

- **Financing Operational Expenses:**
  Cities can benefit from smart parking solutions without bearing the initial financial burden, as these systems can be implemented with minimal upfront costs. This approach ensures that cities begin generating revenue immediately after implementation.

However, the economic component is of particular importance. The cost of parking in densely populated metropolises, for example, in the city of Tbilisi, can reach approximately USD 5,000 or more. Using an area of 21 m² (6 m × 3.5 m), a four-space vertical parking system can accommodate nearly three vehicles per equivalent ground-level parking area.

For comparison, a conventional parking lot occupying 5 m × 6 m (30 m²) accommodates four vehicles, which corresponds to approximately 2.8 vehicles per 21 m². In contrast, a vertical parking system with five spaces can accommodate 3.5 vehicles per 21 m²; with six spaces, 4.2 vehicles; with seven spaces, 4.9 vehicles; with eight spaces, 5.6 vehicles; with nine spaces, 6.3 vehicles; and with ten spaces, up to seven vehicles.

Based on these data, a graph illustrating the dependence of car placement density on the number of parking spaces in a vertical parking system can be constructed Figure 1. Considering that the cost of parking in densely populated urban areas is likely to exceed USD 5,000, and that prices in underground parking facilities are often significantly higher, in some cases approaching residential property prices, the economic advantages of vertical parking systems become evident. The main economic benefits of such systems are summarized below.

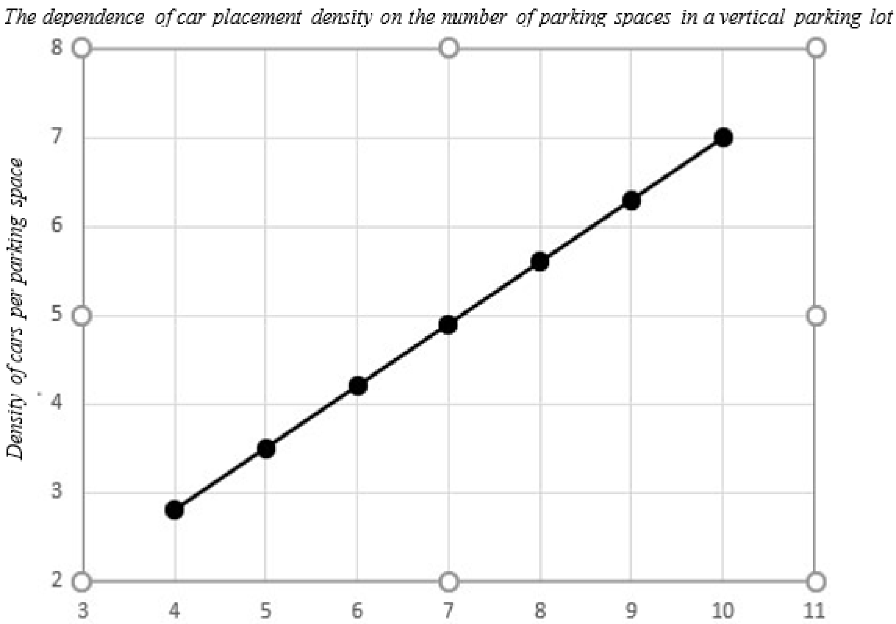

Figure 1 Number of parking spaces in a vertical parking lot

Saving Land Space. This is a key economic factor. Vertical parking systems allow for significantly more cars to be accommodated in the same area compared to traditional surface-level parking lots. For example, on a site where only 2-3 cars would fit, a system for 10-20 cars can be installed. This is especially beneficial in the centers of large cities where land is very expensive.

Reduction of Construction Costs. Compared to the construction of underground or multi-level reinforced concrete parking structures, automated systems made of metal structures can be more economical. Their lighter weight results in lower foundation costs (up to 30% savings) and allows for faster erection.

Reduction of Operating Costs. Automated systems require minimal staff involvement. The absence of the need for a large staff of security guards, cleaners, and parking attendants reduces monthly expenses. Costs for lighting and ventilation are also reduced compared to large underground garages.

Increased Security and Risk Reduction. In closed automated systems, the risk of theft, vandalism, or accidental damage to vehicles is virtually eliminated, since only the owner has access to the cars. This reduces potential expenses for insurance and legal costs.

Investment Attractiveness. Parking spaces in areas with a parking deficit are liquid assets. They can be profitably leased, providing passive income, or resold. The payback period for a vertical parking installation project can be around 3 years, although this indicator strongly depends on specific conditions.

Increased Property Value and Attractiveness. The presence of parking in a residential or office complex directly affects the value and attractiveness of the property. Apartments and offices in buildings with modern parking solutions are sold and rented faster and at higher prices.

A modern metropolis is characterized by narrow streets, dense development, and an eternal lack of free space. In the midst of this maze of concrete, drivers endlessly circle city blocks in search for a free parking spot. The parking problem has evolved beyond mere inconvenience, it has become a significant challenge for residents, businesses, and city authorities alike. Innovative solutions, such as vertical parking systems, are increasingly replacing traditional ground-level parking lots and multi-story parking garages [3-6].

Vertical parking, also known as an Automated Parking System (APS), is a high-tech structure designed for compact and secure vehicle storage using the principle of vertical movement. Unlike conventional parking garages where drivers search for spaces and park themselves, here the process is maximally automated.

Figure 2 shows a foreign analogue of a 12-space parking lot.

The working model of a 4-space vertical parking system has been developed by LLC “Reverse” and manufactured at the “Graal 92” enterprise in Tbilisi. This model is protected under Georgian Patent P 2024 7702 B. Figure 3.

Below is an approximate calculation of the power required for the normal operation of the parking mechanism. The power of the electric motor for rotary parking is determined based on the system’s physical parameters: the combined mass of vehicles and the supporting structure, the lifting speed, and efficiency.

Since the primary motion involves vertical lifting, this factor plays a key role in determining the system’s power requirements [4].

Figure 2 The foreign analogue of 12-space parking

Figure 3 The working model of a 4-space Vertical parking system manufactured according to the project of LLC “Reverse” at “Graal 92” enterprise

2 Literature review

The problem of car parking is very relevant in almost all countries that have a high population density, and it is particularly acute in large cities. In confirmation of this, several citations from a list of publications can be provided.

The article “Smart Parking Systems: A Comprehensive Review of Digitalization of Parking Services” discusses how Smart Parking Systems (SPS) address the limitations of traditional parking methods by providing real-time information on parking space availability, optimizing space utilization, and offering convenient payment solutions. However, despite the relevance and importance of these systems, literature has paid insufficient attention to SPS components that could be significantly improved through innovation. This study addresses this gap by identifying key limitations in [1,2,4] comprehensively analyzed scientific works and proposing innovative solutions. In the field of sensor technologies, environmental impacts and camera line-of-sight issues are addressed through a proposed integrated sensor structure that combines radar precision with camera coverage, enhanced by artificial intelligence to improve detection accuracy.

The article “Understanding Smart and Automated Parking Technology” examines how India’s rapidly growing urban population creates numerous challenges for cities, one of the most persistent being car parking. The number of vehicles is increasing daily, which in turn raises the demand for parking spaces in public areas. In India, as of 2014, there were more than 40 million vehicles, and traffic congestion and insufficient parking spaces remain major issues in most Indian cities.

To address these problems, several new technologies have been developed in recent years to help improve parking efficiency. One such solution implemented in India is the Multi-Level Car Parking System (MLCPS), which optimizes parking space utilization by using vertical rather than horizontal space. The advantages of MLCPS include efficient land use, relatively low construction costs, and reduced operational and maintenance expenses. Although automated parking solutions, such as multi-level parking systems, have improved the situation compared to earlier periods, there is still significant room for improvement. Users continue to experience difficulties related to space availability, search time, and waiting time in public locations such as shopping centers, multiplexes, railway stations, and shopping streets. The implementation of advanced smart parking technologies has the potential to resolve many of these issues [5].

The article “Designing an IoT Smart Parking Prototype System” highlights that, in addition to increased vehicle traffic leading to higher fuel consumption, environmental pollution, and longer travel times, the lack of adequate parking spaces contributes to congestion and traffic accidents. At trip destinations, the need for parking is unavoidable, making parking space an increasingly scarce and expensive resource in urban environments [4].

Materials related to the calculation of load-lifting devices are also relevant and should not be overlooked. In A. A. Reutov’s 2013 article published in the “Bulletin of Bryansk State Technical University”, titled “Calculations of Forces in the Drive-Out Mechanism of a Telescopic Boom”, the distribution of forces, such as weight, wind, and inertial loads, across boom sections is analyzed. This analysis is crucial for the design of cranes and other lifting devices and is based on general principles of structural mechanics for dynamic systems [1].

3 Methodology

Below is an approximate calculation of the power required for the normal operation of the parking mechanism. The power of the electric motor for rotary parking is determined based on the system’s physical parameters: the combined mass of vehicles and the supporting structure, the lifting speed, and efficiency.

Since the primary motion involves vertical lifting, this factor plays a key role in determining the system’s power requirements [4].

Step-by-step method of calculation

1. Determine the load mass:
   Calculate the total mass by summing the weight of the automobiles, the maximum allowable parking load, and the mass of the load-bearing and rotating components of the structure.
2. Select the lifting speed.
3. Specify the efficiency of the drive and gearbox.
4. Substitute the values into the formula and calculate the nominal motor power.

Example of approximate calculation

To calculate the power required for a carousel parking system designed to lift 4 cars, each weighing 2.2 tons, at a speed of 0.05 m/s with an efficiency of 0.9 [8,9], (1), (2):

$$N = \frac{(Q+G)g \cdot v}{\mu}, \tag{1}$$

Where:

- Q - total mass of vehicles, kg;
- G - the mass of the structure, kg;
- g – acceleration of free fall (9,81m/s²),
- v - linear speed, m/s.

$$N = \frac{(8800)9.81 \cdot 0.5}{0.9} = 4796\,WT \tag{2}$$

Based on the calculations, the estimated power requirement for the parking system is approximately 5 kWT.

Practical options:

- A power reserve is necessary to accommodate overload conditions (startup, shutdown, and emergency stops).
- When designing the system, consider both electrical safety and automation requirements.

For specific conditions, individual safety factors are applied, taking into account the actual parameters of the vehicle, the mechanism, and the operating cycle frequency.

It is important to note that our design differs from existing analogues by using a standard chain. In our system, the cradle is suspended directly on the chain links, rather than on a bracket, as is commonly done in Chinese models. This approach significantly reduces friction in the guide elements and decreases stress on the chain nodes. As a result, both operational noise and the required power of the electric drive are significantly reduced.

Figure 4 illustrates the typical cradle suspension scheme used in known prototypes. Due to the fact that the center of gravity of the cradle is offset relative to the chain travel line, the cradle is suspended on a bracket. This is done to reduce the distance between cradles and thereby reduce the height of the structure, which is advisable when a large number of vehicles are placed in the parking system.

Based on the above, additional forces F_1 and F act on the chain, which affect the drive and guide elements. This increases resistance when moving cradles, especially when the chain moves cradles past the drive gears.

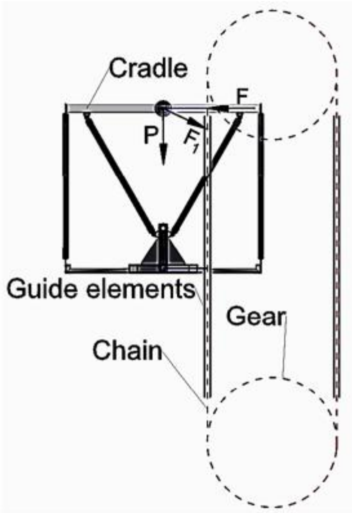

Figure 4 Cradle suspension scheme in a foreign-made vertical parking system

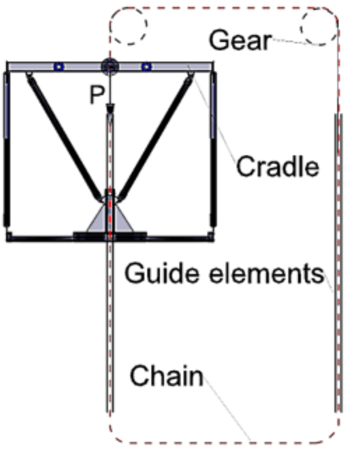

Figure 5 Cradle suspension scheme in the parking system designed by LLC "Reverse"

Figure 5 illustrates the cradle suspension scheme used in the parking system developed by LLC "Reverse". In this design, the cradle's suspension center moves along the chain's travel line, eliminating additional forces that could impede cradle movement. In addition, unlike foreign analogues, the drive gears in our system have a significantly smaller diameter, which significantly reduces the overall construction costs.

Below is an approximate calculation of the frame structure for a 4-space vertical carousel-type parking system [10,11].

Economic report

1. Initial Data

- Structure type: Vertical carousel-type parking (rotary type)
- Number of parking spaces: 4
- Dimensions of one parking space (l × w × h): 5.0 m × 2.5 m × 1.8 m
- Maximum load per cell (vehicle + platform): 2500 kg
- Structure height: ~7 m
- Frame material: Steel (S245, S255)
- Rotation speed: 0.05–0.3 m/s

2. Load Determination

2.1. Vertical Loads

Permanent load (structure weight):

- Steel frames, platforms, mechanisms - approximately 15–20% of useful load.

- Total structure weight:

$G_k = 4 \times 2500 \times 0.2 = 2000$ kg

- Useful load (cars):

$G_a = 4 \times 2500 = 10000$ kg

- Total vertical load:

$N = G_k + Ga = 2000 + 10000 = 12000$ kg ≈ 120 kN

2.2. Horizontal (wind) loads

For a height of 8 m (standard wind pressure value ~ 0.38 kPa):

$F_w = 0.38$ x 5 x 8 = 15.2 kN

2.3. Dynamic loads (during rotation)

- Centrifugal forces:

$F_c = m \cdot \omega^2 \cdot R,$

where

- $\omega = \frac{v}{R} = \frac{0.05}{0.5} = 0.1 rad/s$
- R = 0.5 m (rotation radius)
- m = 2500 kg (car + platform combined mass)
- $F_c = 2500 \cdot 0.1^2 \cdot 0.5 = 12.5\, N$(slightly)

3. Frame elements calculation

3.1. Columns (supports)

- Load per column (4 columns in the structure):

$$N_k = \frac{120}{4}\text{=30kN}$$

- Section selection (steel tube or I-beam):

$$\sigma = \frac{N}{A} \leq R_y = 240 mPa$$

$$A \geq \frac{N}{\varphi \cdot R_y} = \frac{46.29 \cdot 10^3}{0.5 \cdot 240 \cdot 10^6} = 3.86 \cdot 10^{-4} m^2 = 3.86 cm^2$$

$$\sigma = \frac{46.29 \cdot 10^3}{0.5 \cdot 240 \cdot 10^6} 3.86 \cdot 10^{-4} m^2 \sim 3.86 MPa < 240 MPa$$

A minimal cut set: tube ⌀150x5 mm (A ≈ 22.8 ^2 \)).

4. Conclusion

The frame of a vertical carousel-type parking system can be made of:

- Columns: steel tubes ⌀150x5 mm.
- Beam heads: I-beams No. 20.
- Foundations: reinforced concrete slabs 0.8×0.8 m.

For accurate calculation, detailed development of joints (platform mounting, drives) and consideration of seismic factors (if necessary) is required.

1. The load-bearing frame consists of 4 steel tubes ⌀150×5 mm with braces.
2. Ring beams are made of I-beam No. 14.
3. Foundations 1.5×1.5 m provide stability against wind overturning.
4. Dynamic loads are insignificant at rotation speed ≤0.3 m/s.

Important: for a real project, it is required to:

- Consider seismic factors (if applicable)
- Check platform mounting joints
- Perform calculations according to SP 16.13330.2017
- Account for snow load on the roof.

Unlike existing foreign constructions, the presented system is capable of movement in both vertical and horizontal directions. This feature enables the construction of parking facilities that adapt to the mountainous landscape that is prevalent in Georgia.

Figure 6 shows a balcony parking system, a mechanized garage with an elevator and movable hangers in the vertical and horizontal planes. P 2021 7228 B.

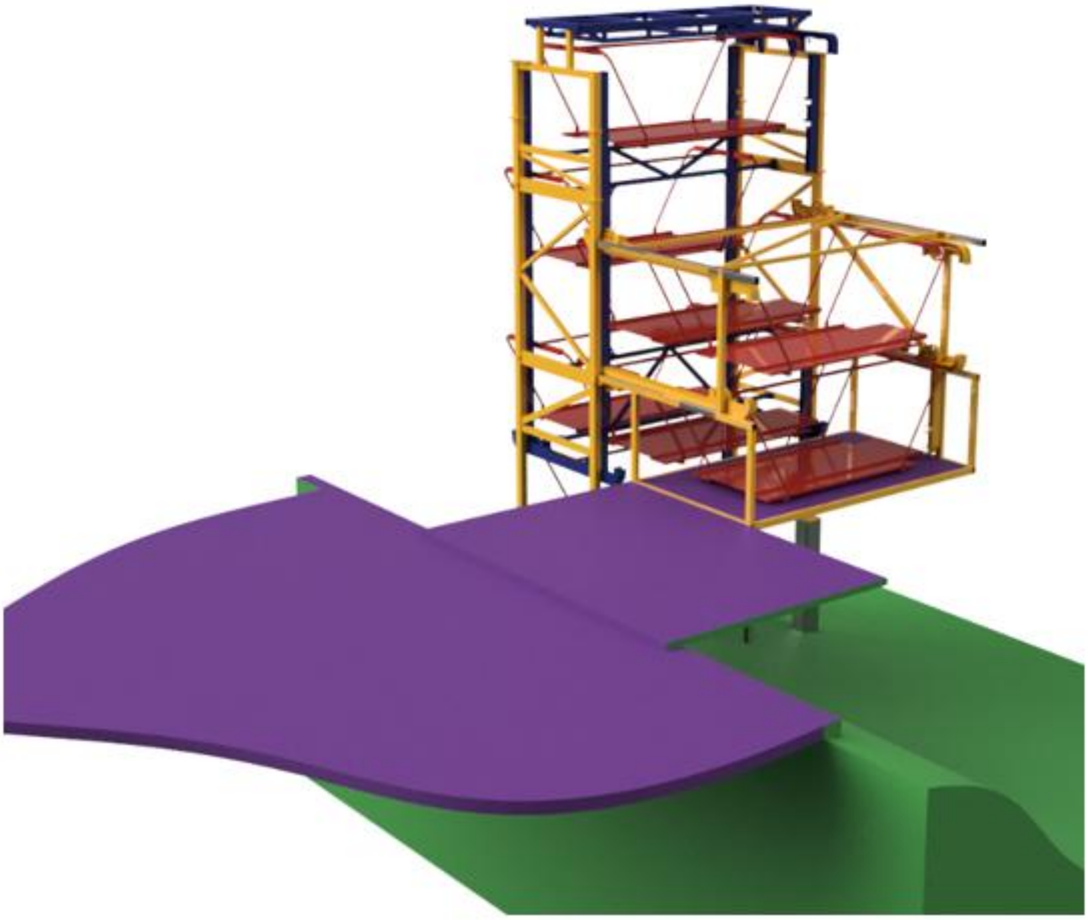

Figure 6 The balcony parking system Mechanized garage with elevator and movable cradles in vertical and horizontal planes

4 Results and discussion

The balcony parking system is a hybrid solution that offers a key advantage: the ability to utilize complex and space-constrained landscapes for organizing parking. Vehicles enter the system through a specially designed balcony platform, allowing the installation of parking facilities on virtually any slope.

The vertical-horizontal (hybrid) parking system combines the features of both vertical and horizontal systems, enabling efficient use of complex terrains for organizing parking spaces. Its main advantage is the simultaneous utilization of vertical and horizontal space, which allows for the accommodation of more vehicles in areas with difficult terrain. Figure 7.

The horizontal parking system is essentially a 90-degree rotated adaptation of the vertical system, designed for efficient vehicle parking on both flat surfaces and inclined terrains. Figure 8.

A car parking lift comprising metal load-bearing vertical support columns formed in the form of a Π-shaped guide, a lifting platform for raising the automobile, a hydraulic drive implemented as a hydraulic compressor and hydraulic cylinder, which is connected to flexible lifting elements mounted on pulleys. In addition, to maintain the balance of the platform, a slide bar is inserted with the ability to slide in each column of the lift, where each slide bar contains at least one spring-loaded eccentric cam mounted with the ability to rotate on an axle, and a conical wedge connected to it and equipped with an emergency displacement spring, which is mounted on the flexible lifting element, while the automobile lifting platform is mounted on the slide bar. Also, the flexible lifting elements mounted on pulleys are connected to a pulley mechanism of a polyspast, which is horizontally positioned at the base of the lift structure and is connected to a drive, which in turn comprises emergency automatic brakes and an electronic control system.

The technical result is an increase in the reliability and stability of the device, improvement of operational efficiency, simplification of the construction, and reduction of economic costs. The reliability and stability of the device is achieved by the fact that the columns have a special Π-shaped form, in which the carriage moves with the ability to slide, and the latter is equipped with a spring-loaded eccentric cam, which in the case of rotation relative to the axle comes into engagement with a conical pawl mounted on the lifting flexible element, which simplifies the construction and reduces economic costs.

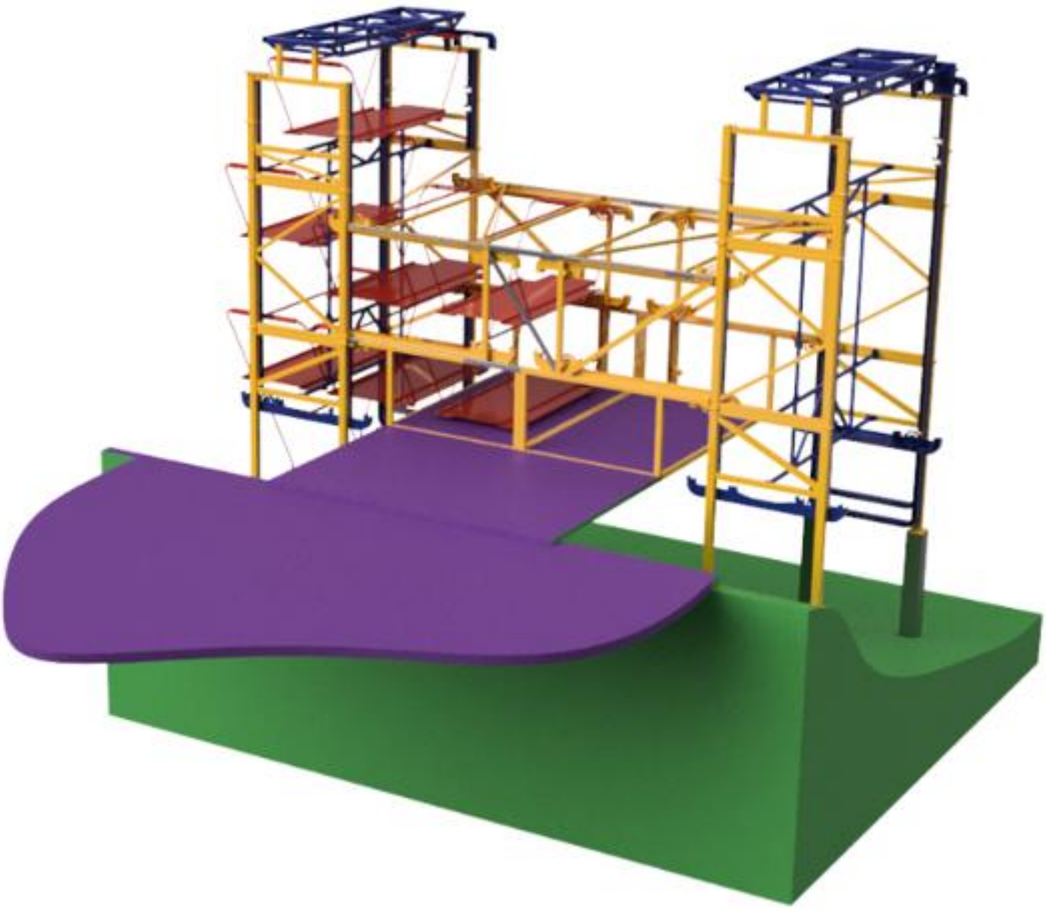

Figure 7 The vertical-horizontal parking system

However, the economic component is of particular importance. The cost of parking in densely populated metropolises, for example, in the city of Tbilisi, can reach approximately USD 5,000 or more; while using an area of 21 m² (6 m × 3.5 m), a four-space vertical parking system can accommodate nearly three vehicles per equivalent ground-level parking area.

If a parking lot occupies an area of 5m × 6m = 30m² and can accommodate 4 cars, then on an area of 21m² it is possible to accommodate 2.8 cars. With a 5-space system, 3.5 cars can be accommodated; with 6 spaces - 4.2 cars; with 7 spaces - 4.9 cars; with 8 spaces - 5.6 cars; with 9 spaces - 6.3 cars; with 10 spaces - 7 cars. If we consider that the cost of a parking space in densely populated urban areas will exceed $5,000, and in underground garages the price will be significantly higher - in some places it is practically equivalent to the cost of apartments - then the benefit here is obvious. On a site where only 2-3 cars would fit, a system for 10-20 cars can be installed. This is especially beneficial in the centers of large cities. Compared to the construction of underground or multi-level reinforced concrete parking structures, automated systems made of metal structures can be more economical. They require lower foundation costs (up to 30% savings) due to the lighter weight of the structures and can be erected faster. Automated systems require minimal staff involvement. Costs for lighting and ventilation are also reduced compared to large underground garages. In closed automated systems, the risk of theft, vandalism, or accidental damage to vehicles is virtually eliminated, since only the owner has access to the cars. This reduces potential expenses for insurance and legal costs. Parking spaces in areas with a parking deficit are liquid assets. They can be profitably leased, providing passive income, or resold. The payback period for a vertical parking installation project can be around 3 years, although this indicator strongly depends on specific conditions. The presence of parking in a residential or office complex directly affects the value and attractiveness of the property. Apartments and offices in buildings with modern parking solutions are sold and rented faster and at higher prices.

Figure 8 Vertical parking with horizontal vehicle arrangement

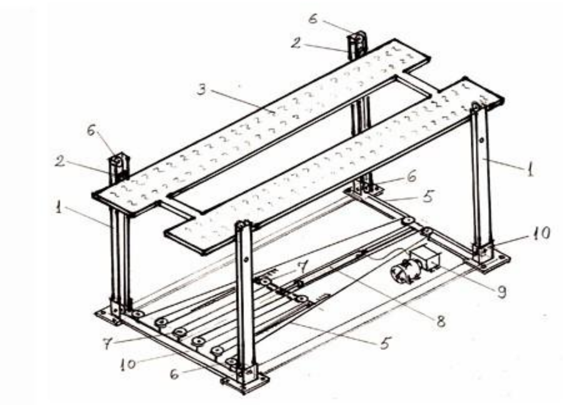

Figure 9 Schematic representation of a parking lift with corresponding kinematics

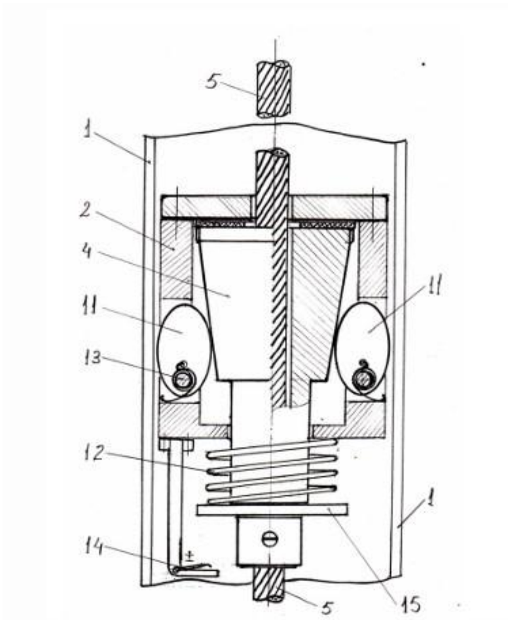

Figure 10 A slider inserted into a column with appropriate structural elements to allow sliding

Figure 9 illustrates a schematic representation of the car parking lift with corresponding kinematics.
Figure 10 shows a slider inserted with the possibility of sliding in the column with corresponding structural elements.

5 Conclusion

Vertical parking is more than just a technological innovation; it is a practical and increasingly essential solution for cities struggling with traffic congestion and limited space. Despite the high cost and technical nuances, its key benefits, such as substantial land savings, enhanced vehicle security, and improved user convenience, make it an attractive option for urban planners and developers alike [12]. This is a forward-looking step in urban infrastructure, where efficiency and convenience converge [13]. As technology evolves and implementation costs decline, vertical parking systems will become as a familiar element of the urban landscape as multi-story garages once were.

This article presents the results of the design, calculation, and manufacturing of a vertical parking structure. Vehicle movement, along with the platforms, is achieved in both vertical and horizontal directions using a chain-driven transmission system. The structure comprises a frame, chain drive, guide rails, and a control unit, which manages platform positioning and enables vehicle entry and exit from the parking system.

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Review process

Single-blind peer review process.