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TECHNICAL FOUNDATIONS OF ELECTRIC DRIVE, DIGITAL DOCUMENTATION AND SAFETY MODERNIZATION IN BRINGING RETRO AUTOMOBILES BACK TO LIFE

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Abstract. The article analyzes the process of bringing retro automobiles back to life in terms of restoration, electrification, digital documentation and safety modernization in automotive engineering. The purpose of the study is to substantiate the possibilities of improving energy efficiency, environmental indicators and traffic safety while preserving authenticity when returning historically valuable passenger cars to operation. The methodology used literature analysis, structural-diagnostic criteria, a computational energy model and a life-cycle approach. The results showed that in a retro automobile converted to electric drive, operating costs under urban conditions decrease significantly, direct exhaust gases are eliminated, and the reliability of the restoration process increases through digital passportization. However, battery placement, mass distribution, high-voltage protection and homologation requirements should be regarded as mandatory technical control.

Keywords: retro automobile, restoration, EV retrofit, electric drive, BMS, digital passport, safety modernization, life-cycle analysis.

INTRODUCTION. In the history of automotive engineering, retro automobiles are important not only as means of transport, but also as technical heritage reflecting the engineering culture, design school and industrial approach of a certain period. It is not sufficient to keep such automobiles only in a simple preserved form; returning them to operation in a technically safe, environmentally acceptable and economically useful condition is one of the urgent issues facing modern automotive engineering. For this reason, a separate service market is forming worldwide for the restoration of classic automobiles, conversion to electric drive, digital passportization and remanufacturing of spare parts [1].

Bringing a retro automobile back to life requires the simultaneous harmonization of two opposing requirements. The first requirement is related to preserving the historical appearance, structural features and collectible value of the automobile. The second requirement is adaptation to the modern operating environment, that is, improvement of traffic safety, ecology, energy consumption, diagnostics and maintenance capabilities. If restoration is limited only to restoring the exterior appearance, such an automobile may not be sufficiently reliable for daily or tourist use. Conversely, if modernization is carried out too deeply, the historical authenticity of the automobile is lost.

In recent years, scientific research on converting vehicles with internal combustion engines to electric drive has been increasing. The environmental benefit of retrofit electrification is explained not only by reducing exhaust gases, but also by reducing the material and energy consumption at the stage of producing a new automobile through reuse of the existing body and chassis resource [2]. Such an approach corresponds to the principles of the circular economy, because the existing asset is not fully disposed of, but is returned to a renewed value chain.

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The purpose of this study is to develop the scientific and technical foundations of restoration, conversion to electric drive, digital documentation and safety modernization used in bringing retro automobiles back to life, and to assess their environmental and economic efficiency through a computational model. As the object of the study, a generalized model of a classic passenger car with a mass of 1000-1200 kg was adopted. The subject of the study is the relationship between structural decisions, energy consumption, safety requirements and operating costs in the process of technical restoration and electrification of this automobile.

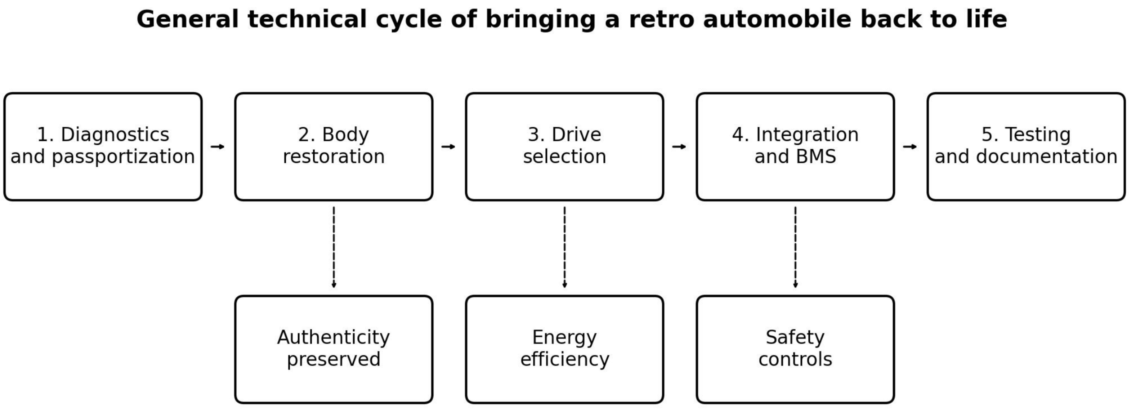

Figure 1. General technical cycle of bringing a retro automobile back to life

LITERATURE REVIEW

The literature review shows that the issue of bringing a retro automobile back to life is closely connected not only with automobile restoration, but also with such areas as electromobilization, environmental assessment, structural safety, digital traceability and service economics. Thammasiriroj and co-authors considered classic automobiles as a separate growth point for the EV conversion industry and substantiated the importance of state policy, consumer acceptance and local industrial clusters in such projects [1]. This approach makes it possible to view retro automobile modernization not as narrow workshop practice, but as an industrial-service ecosystem.

The environmental benefit of electric retrofit was assessed in the study by Innocenti and co-authors through life-cycle analysis. They show that, in some scenarios, electrifying an existing urban vehicle instead of purchasing a new automobile can significantly reduce greenhouse gas emissions [2]. At the same time, the authors emphasize that the retrofit result is sensitive to the composition of electricity generation, battery service life and the recycling process. This conclusion indicates that in retro automobile projects it is necessary to take into account not only technical integration, but also the energy source and service infrastructure.

Kryzia and Kryzia assessed the economic feasibility of converting passenger cars powered by internal combustion engines into electric vehicles using the Monte Carlo approach and showed that conversion can be economically justified under certain technical and price conditions [3]. Aggarwal and Chawla analyzed the practical process of converting a gasoline-engine vehicle into a battery electric vehicle and identified motor, battery, control system and transmission compatibility as the main selection factors [4]. These developments are also important for a retro automobile, because in older automobiles the issues of body strength, the condition of the wiring network and integration with the mechanical gearbox become even more complex.

In terms of operating economics, Sendek-Matysiak and Grysa showed the necessity of comprehensively taking into account factors such as purchase price, energy price, service and residual value when assessing the total cost of ownership of electric vehicles [5]. The same logic is also applied when electrifying a retro automobile, but in addition, factors such as collectible value, restoration quality, spare parts availability and the reliability of project documentation also become important.

Table 1. Summary of scientific approaches to bringing a retro automobile back to life

Direction	Main scientific idea	Application to a retro automobile	Source
EV conversion industry	Electrification of classic automobiles creates a separate market and service chain.	Workshop, engineering design and homologation services are integrated.	[1]
Life-cycle analysis	Retrofit reduces GHG in some scenarios compared with producing a new automobile.	Reuse of the existing body and chassis provides an environmental advantage.	[2]
Economic assessment	The effect of conversion depends on energy price, driving distance and conversion cost.	Payback and TCO calculations should be performed before the project.	[3], [5]
Technical integration	Compatibility of the battery, motor, inverter and transmission determines project success.	Mass distribution and high-voltage safety are checked separately.	[4]
Digital documentation	Reliable records of restoration traces and original parts increase value.	A digital passport, photo archive and service history are created.	[12]

Aerodynamic and energy studies in automotive engineering are also directly important in retro automobile projects. Alam and co-authors analyzed the issues of aerodynamic drag and thermal cooling in passenger cars in connection with energy saving [6]. Qin and co-authors showed the influence of CFD parameters on results for the DrivAer model and substantiated the importance of mesh quality and the turbulence model in digital testing [9]. Aultman and co-authors compared CFD results with wind tunnel testing for an SUV body and noted that some RANS models do not provide design trends with sufficient accuracy in strongly separated flows [10]. Since the body shape of retro automobiles is usually less optimized than that of modern automobiles, reducing aerodynamic drag, arranging wheel arches and improving underbody flow can have a significant effect on energy consumption.

Regarding digital documentation, Murta and co-authors proposed a blockchain-based trusted record system for the restoration of classic automobiles [12]. This approach makes it possible to store the authenticity of a retro automobile, the history of the work performed, replaced parts and safety tests in a non-falsifiable manner. In this respect, in the process of

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bringing a vehicle back to life, creating an electronic service passport in addition to mechanical restoration should also be considered as a scientific and practical requirement.

METHODOLOGY

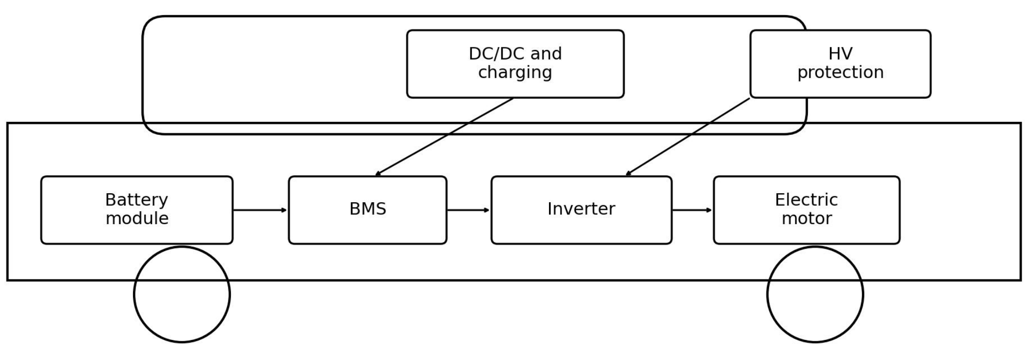
The research methodology was structured as consisting of the stages of literature analysis, structural-diagnostic assessment, computational energy model, life-cycle approach and safety risk assessment. The calculations in this article were performed for a sample retro passenger car in the form of an analytical model. That is, the results are interpreted not as a real laboratory test, but as an engineering model showing a preliminary technical project assessment.

At the first stage, the body, frame or load-bearing body elements, suspension, braking system, steering, electrical network and transmission elements of the automobile are diagnostically assessed. Corrosion, welded areas, deformation, door and pillar geometry, and front and rear suspension mounting points are checked separately in the body. If the residual strength of the load-bearing elements is insufficient, structural restoration must be performed before moving to electrification. This is because the battery and electric drive elements change the mass and center of gravity of the automobile.

At the second stage, the electric drive architecture is selected. In this article, for the generalized retro automobile, a 60 kW electric motor, a lithium-ion battery with a nominal capacity of 28 kWh, an inverter, BMS, DC/DC converter, on-board charging device and high-voltage protection system were adopted. The useful capacity of the battery was assumed to be 90%. This makes it possible to assess the calculated driving range of 130-210 km in urban and mixed modes.

Energy consumption was assessed based on the following road resistances: aerodynamic drag, rolling resistance and inertia losses in acceleration mode. Aerodynamic drag was adopted using the expression $Fd = 0.5 \cdot rho \cdot Cd \cdot A \cdot v^2$, while rolling resistance was adopted as $Fr = m \cdot g \cdot f$. Here rho is air density, Cd is the aerodynamic drag coefficient, A is the frontal area, v is speed, m is automobile mass, g is gravitational acceleration, and f is the rolling resistance coefficient. For operating costs, gasoline consumption was assumed to be 9.5 l/100 km, gasoline price 12,000 soums/l, electricity consumption 18.5 kWh/100 km and electricity price 1,000 soums/kWh.

Conceptual architecture of an electrified retro automobile



Note: the diagram shows the general structural layout; the real project is specified based on the model, homologation and safety requirements.

Figure 2. Conceptual architecture of an electrified retro automobile

Table 2. Main parameters adopted in the computational model

Indicator	ICE restoration	EV retrofit	Note
Automobile	1050	1180	Mass increases

mass, kg			due to the battery and electrical equipment
Engine power, kW	55	60	Sufficient level for urban and mixed use
Energy source	Gasoline	28 kWh battery	Useful capacity was assumed to be 25.2 kWh
Energy consumption	9.5 l/100 km	18.5 kWh/100 km	Calculated assumption for mixed urban mode
Direct exhaust gases	Present	0	There are no tailpipe exhaust gases in EV retrofit
Main risk	Fuel and aged wiring network	High voltage and battery heating	Safety inspection is required in both variants

In the safety assessment, four areas were distinguished: high-voltage safety, mechanical protection of the battery, compatibility of the braking and suspension systems with the new mass, as well as energy disconnection in an emergency situation. As a minimum functional requirement, the BMS must monitor the voltage, current, temperature, state of charge and fault status of each module. High-voltage cables are routed along paths protected from mechanical damage and are protected by a service disconnect and emergency relays.

In the digital documentation methodology, the initial condition of the automobile, VIN or identification marks, body geometry, materials used during the restoration process, replaced parts, electrical diagrams, battery passport, test reports and maintenance history are collected in a single electronic folder. Such documentation increases the vehicle's later resale value, transparency in service and convenience of working with regulatory authorities.

DISCUSSION AND RESULTS

The results of the computational model showed that the greatest efficiency in bringing a retro automobile back to life arises at the operating stage. In the ICE restoration variant, the automobile is preserved close to its historical original, but fuel consumption remains high in urban traffic and exhaust gases remain. In the EV retrofit variant, direct exhaust gases are eliminated, noise is reduced and the maintenance interval is simplified. However, battery mass, its placement and high-voltage safety require structural analysis.

In the calculations, the ICE restoration variant was assumed to consume 9.5 liters of gasoline per 100 km. At a price of 12,000 soums/l, this equals 114,000 soums of operating energy cost. If the EV retrofit variant is assumed to consume 18.5 kWh of electricity per 100 km, then at a price of 1,000 soums/kWh the cost amounts to 18,500 soums. Thus, based only on energy costs, the EV retrofit variant provides savings of 95,500 soums per 100 km. If the conversion cost is assumed to be around 80 million soums, the conditional payback distance is in the range of 83-85 thousand km. This result depends significantly on energy prices, battery cost and annual mileage.

In the environmental comparison, in the ICE variant, tailpipe CO_2 emissions were estimated at around 219 g/km based on the coefficient of 2.31 kg CO_2 per 1 liter of gasoline. In the EV retrofit there are no direct exhaust gases, but there are indirect emissions related to the source of electricity generation. If grid emissions are assumed to be 0.45 kg CO_2e/kWh, then with a consumption of 18.5 kWh/100 km, indirect emissions are around 83 g/km. If the share of

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renewable energy is high, this indicator can decrease to 15 g/km. Therefore, electrifying a retro automobile provides environmental benefit, but the result is highly dependent on the electricity source.

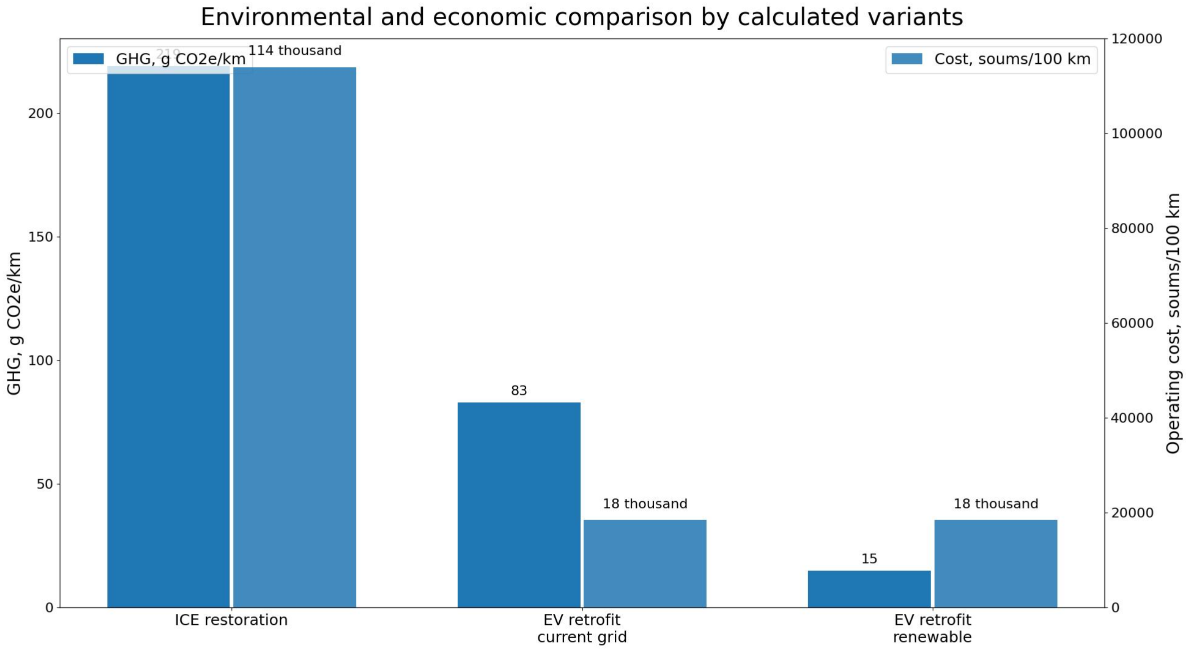

Figure 3. Environmental and economic comparison by calculated variants

Table 3. Comparative assessment of the variants for bringing a vehicle back to life

Criterion	**Traditional restoration**	**EV retrofit**	**Hybrid approach**	**Note**
Historical authenticity	High	Medium	High-medium	The original motor may be removed during electrification
Environmenta l benefit	Low	High	Medium	The source of electricity is important
Operating cost	High	Low	Medium	Determined by service and energy price
Safety control	Mechanical and fuel system	HV, BMS, battery protection	Control of both types	Depends on the depth of modernization
Market value	Depends on authenticity	Innovative segment	Wider audience	Documentatio n increases value

The effect of speed on energy consumption was analyzed separately. In the range of 40-60 km/h, the calculated energy consumption of the electrified retro automobile was relatively low and was estimated in the range of 12.0-14.5 kWh/100 km. When the speed increased to 100-120 km/h, aerodynamic drag increased according to the square law, and energy consumption rose to 23.8-30.5 kWh/100 km. This is explained by the fact that the body shape of retro automobiles is less optimized aerodynamically compared with modern automobiles. Therefore, using an electrified retro automobile on urban and tourist routes is more appropriate from an energy perspective.

Battery placement is one of the main factors determining project quality. If the battery is concentrated excessively in the front or rear part, the center of gravity shifts, the dynamic load distribution during braking changes, and cornering stability may decrease. The most appropriate approach is to place the battery modules in a balanced manner under the floor, in the central tunnel or in the lower part of the trunk. In this case, the requirements for corrosion protection, prevention of water ingress, ventilation and fire safety must be met.

The discussion results show that there is no single universal solution for bringing a retro automobile back to life. In an automobile with very high collectible value, mechanical restoration while preserving the original engine may be preferable. For a mass-produced automobile whose spare parts are difficult to find but whose body is well preserved, an EV retrofit is appropriate. For medium-value automobiles, a hybrid approach, that is, preserving the exterior and interior appearance as original while modernizing the brakes, steering, electrical network and safety elements, is an effective solution.

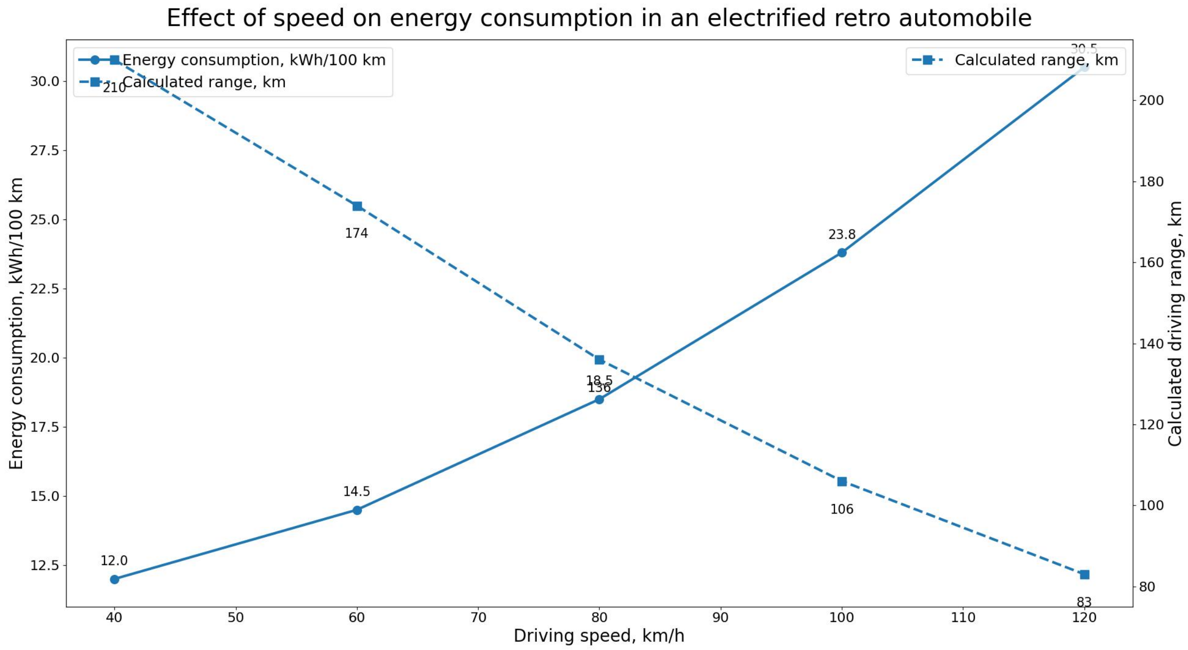

Figure 4. Effect of speed on energy consumption and driving range in an electrified retro automobile

Table 4. Main risk factors and control measures for an electrified retro automobile

Risk factor	Cause of origin	Consequence	Control measure
Battery heating	Incorrect ventilation or excessive current	Reduction of battery life and safety risk	BMS, thermal sensor, fuse and cooling channel
High-voltage damage	Routing of the cable without mechanical protection	Electric shock or short circuit	HV interlock, service disconnect, protected channel
Disturbed mass distribution	Battery placement on one side	Braking and cornering stability deteriorate	Calculation of front-rear and left-right mass distribution
Insufficient braking system	Increase in automobile mass	Braking distance increases	Compatibility of disc/pad, hydraulics and regenerative

			braking
Lack of documentation	Restoration process performed without records	Problems in service, sale and authorization	Digital passport and test reports

Digital documentation creates separate economic value in retro automobile projects. In the classic automobile market, the buyer mainly pays attention to the true history of the vehicle, the share of original parts, the quality of the restoration performed and evidence of maintenance. If all data are stored in an electronic passport, confidence in the technical condition of the automobile increases. This not only increases resale value, but also serves as a clear technical guideline for service workshops.

In addition, bringing retro automobiles back to life can serve as a practical laboratory for local automotive education and small business. Such projects combine welding, painting, metalworking, electrical diagrams, BMS, mechatronics, automobile diagnostics, digital modeling and 3D-printed parts. Therefore, a retro automobile project is not only the restoration of a single vehicle, but also a tool for developing automotive competencies.

The limitation of the study is that the calculations were performed on the basis of generalized parameters. For a real project, the exact automobile model, body condition, brand of electrical components, battery type, road test results and national homologation requirements must be determined separately. Nevertheless, this methodological approach provides a useful basis for comparing technical decisions, arranging risks and assessing economic feasibility at the preliminary project stage.

CONCLUSION

Bringing retro automobiles back to life is a complex engineering process that combines the areas of restoration, electrification, safety modernization and digital documentation in automotive engineering. The methodological approach developed in the study showed the need to create a balance between preserving the historical authenticity of the automobile, increasing its technical safety and improving its operating efficiency.

According to the calculated results, the ICE restoration variant preserves the historical appearance at a high level, but has limitations in terms of fuel consumption and exhaust gases. The EV retrofit variant, on the other hand, eliminates direct exhaust gases and reduces energy costs. Under the model conditions, the energy cost per 100 km may decrease from 114,000 soums to 18,500 soums. However, this solution makes it mandatory to recalculate battery placement, BMS, high-voltage protection, mass distribution and the braking system.

Digital passportization and documentation based on blockchain or immutable records serve as an important tool for preserving the technical history, authenticity and market value of a retro automobile. It is recommended that each restoration stage be formalized with photographs, measurements, drawings, spare part codes and test reports.

In practical terms, bringing retro automobiles back to life can create a new direction for local service workshops, automotive education, spare parts production and tourist transport services. In the future, it is advisable to carry out an expanded study that includes experimental braking tests, battery thermal tests, road energy consumption measurements and homologation requirements for a specific automobile model.

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