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# COMPETITIVE COST ANALYSIS OF ALTERNATIVE POWERTRAIN TECHNOLOGIES

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**Abstract**
This paper examines the cost competitiveness of different electrified propulsion technologies from hybrid cars to full battery electric vehicles in the time horizon 2010 to 2020. The assessment shows that the current TCO gaps for alternative drivetrains will increasingly converge over time mainly driven by decreasing production cost. However, the cost-efficiency of different powertrain architectures depends highly on the mileage a user expects to drive per year. In the mid-run, hybrid electric vehicles (especially with external charging) will be an attractive option in particular for users with high annual mileages, who can benefit from the low operating cost of EVs in combination with unlimited driving range. The analysis concludes that there will be a variety of competing drivetrain architectures in the market, which in turn leads to increased risk and complex decision making for the portfolio of automotive OEMs and suppliers.

## Introduction

Driven by ambitious $CO_2$ reduction targets and a growing awareness for fuel economy by the customer, automotive OEMs are increasingly required to develop energy efficient vehicles. In this context electrification of the automotive powertrain is the most important lever to reduce green house gas emissions and energy consumption of passenger cars. A variety of propulsion concepts from mild hybrid to full electric cars has been developed and will be introduced into the market over the next years. However, the question which technology will be accepted by the user and hence will prevail in the long run has not been answered, yet.

Hence, the objective of this paper is to examine the cost competitiveness of different electrified propulsion technologies. The analysis covers all basic powertrain architectures, from conventional cars with internal combustion engines (ICE), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) to extended range electric vehicles (EREV) and full battery electric vehicles (BEV). A holistic cost assessment has been performed for drivers with varying annual mileages to decide which powertrain is cost optimal for which type of user. This analysis has been repeated for several points in time to allow a fact-based outlook into the future market development.

## Methods

As alternative propulsion technologies usually have higher initial purchase prices but lower operating costs, a life cycle perspective is required when comparing them to conventional vehicles. This paper comprehensively analyzes the total cost of ownership (TCO) from initial purchase to resale of the car. Five different powertrain concepts are explored to cover the full range of technologies. The drivetrain architecture and basic parameters of the analyzed vehicle concepts are summarized in Table 1. The assessment focuses on passenger cars in the medium segment purchased and operated in Germany. The gasoline powered ICE car serves as reference vehicle. Its configuration, weight, retail price, fuel consumption etc. matches with the average midsize passenger car sold in the German auto market in 2010 according to ADAC and KBA data.[1,2]

| Parameter | Unit | Powertrain technology | | | | |
|---|---|---|---|---|---|---|
| | | ICE | HEV | PHEV | EREV | BEV |
| Vehicle architecture (Midsize car segment) | | Gasoline engine, 2-wheel drive (identical for all), 6-speed transmission | Parallel hybrid with 2 cluches, 6-speed transmission | Parallel hybrid with 2 cluches, 6-speed transmission external charge unit | Series hybrid, single-speed transmission, external charge unit | Central electrical traction motor, single-speed transmission |
| Power combustion engine | kW | 100 | 100 | 100 | 50 | - |
| Power e-motor | kW | - | 25 | 50 | 100 | 100 |
| Electrical energy storage | kWh | - | 2 | 5 | 15 | 30 |
| Curb weight | kg | 1400 | 1507 | 1576 | 1628 | 1621 |
| Aerodynamic drag coefficient | - | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| Frontal area | $m^2$ | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| Rolling resistance | - | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

**Table 1:** Vehicle setup and parameterization

To determine the **energy consumption** of the selected powertrain concepts the DLR proprietary Modelica library *AlternativeVehicles* is applied.[3] The software contains parameterized drivetrain components (e.g. electric drives, transmissions, batteries) to build up and model different vehicle architectures. The simulation allows analyzing the dynamic system behaviour during driving. Several standardized driving cycles (e.g., NEDC or Artemis) are used to examine and compare the energy efficiency of the powertrain concepts under varying conditions.

The simulation results are integrated in an extensive **total cost of ownership model**. The TCO analysis covers all types of expenses accruing for a vehicle owner including one-time cost (e.g., purchase price, expected resale value) as well as operating cost (e.g., fuel/energy, vehicle tax, general/exhaust inspection, maintenance, and repair). Figure 1 provides an overview of the general structure of the TCO model. Unlike previous TCO analyses the model is flexible in annual mileage, holding period, and use characteristics (i.e., share of urban vs. highway driving).[4,5,6] This approach facilitates the economic comparison for different types of users as well as it allows performing a great range of sensitivity analyses.

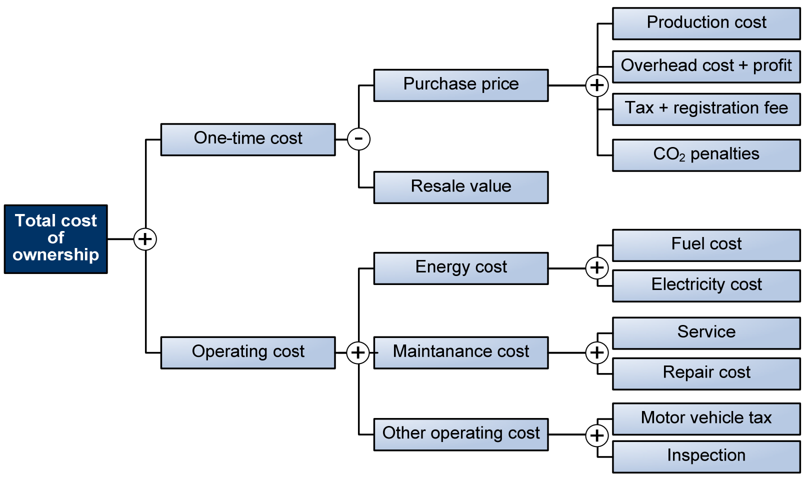


**Figure 1:** Structure of the TCO-model

The **production cost** of the powertrain components are based on a proprietary *McKinsey* study.[7] In this study, the future cost development of over 60 drivetrain components have been analyzed by consolidating industry data, expert interviews, and economic forecasts. The basic car body, interior, and chassis (excluding powertrain) is assumed to be identical for all examined vehicle concepts. For the most expensive and crucial part of electric powertrains, the traction battery, a detailed cost model has been developed. This *DLR battery model* allows estimating cell, module, and pack prices for the most important Li-ion chemistries. (In this analysis NMC has been selected for high-energy storages and NCA for high-power configuration.) A learning curve for the price development of Li-ion batteries has been derived by applying the cost model for different output levels. The analysis indicates a cost decrease of 14% for a doubling of the cumulated production of high energy batteries, which are used for PHEVs, EREVs, and BEVs. This implies that the battery price (for a BEV) will decrease from ca. EUR 860 per kWh on pack level in 2010 to below EUR 250 per kWh, if the national target of 1 million EVs in 2020 set by the German government can be achieved.

For all other **external influence factors** realistic scenario assumptions have been made. For example the assumed oil price development reflects the *current policy scenario* published in *IEA World Energy Outlook 2011*, which projects a moderate increase to 118 USD/barrel by 2020.[8] Electricity costs are based on expected distributer prices for Germany as specified in the 2010 study of the German *Federal Environment Ministry*.[9]

The European Union **$CO_2$ emission target** of 120 g/km will start in 2012 and decline to 95 g/km by 2020. If the fleet average of an automotive manufacturer exceeds this $CO_2$ limit (corrected by a weight-depended factor), a penalty of 95 per g $CO_2$/km has to be paid, which is included in the TCO calculation.

In Germany – as of today – the only direct **monetary incentive** from government side is the motor vehicle tax exemption for BEV holders with savings of approximately EUR 50 per year. Other benefits or subsidies for EVs as proposed by the *National Platform Electromobility* have not been decided yet, and therefore are not incorporated in the TCO model.[10]

In this simplified approach the **depreciation** of newly purchased vehicles only depends on the vehicle miles travelled, assuming an identical holding period of 4 years for all vehicles. The extensive ADAC database on resale values serves as data source to calibrate the model for the medium size vehicle segment.[1] Net present values of the resale values after 4 years have been calculated assuming a discount rate of 5%. For a more detailed model on resale values of different drivetrain architectures and vehicles sizes see *Propfe (2012)*.[11]

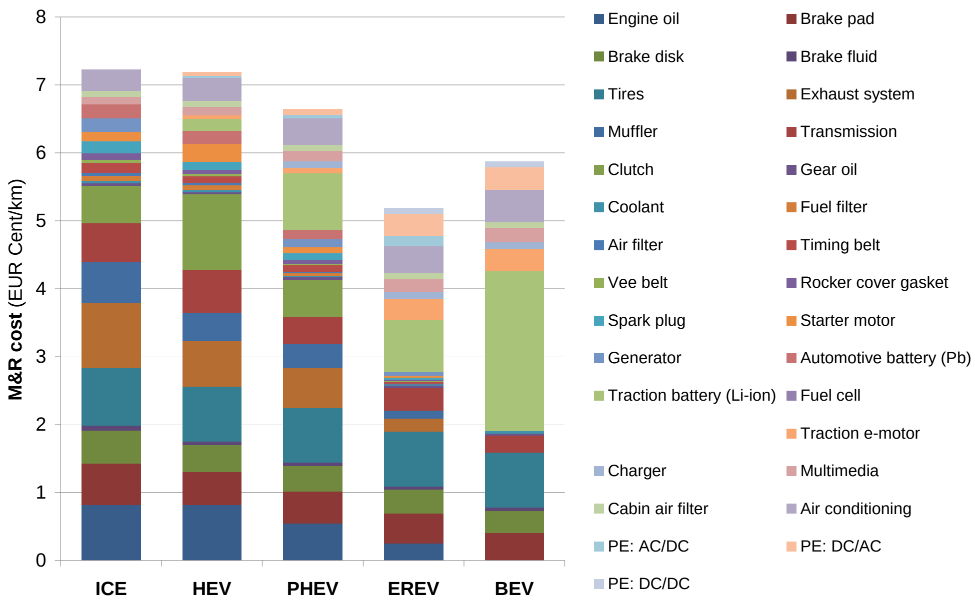


**Figure 2:** Maintenance and repair cost in EUR/km for the medium car segment
[Source: DLR analysis]

To determine **maintenance and repair costs** on a EUR per km level more than 30 drivetrain components have been evaluated in terms of mean times between failure, material cost, and required labor input based on ADAC data. The bottom-up model incorporates different drivetrain architectures, ranging from conventional ICEs to hybrids and full electric vehicles. Hybrids are differentiated into serial and parallel hybrids, with two different parallel hybrid architectures (torque adding hybrids and axle-split hybrids). Serial hybrids are defined as ideal serial hybrids with the electrical motor as single driving motor. All hybrids are definable as grid connected with external charging unit or non-grid connected hybrids. The results of the maintenance and repair model are presented in Figure 2. The drivetrain architecture has been chosen to resemble the vehicle parameterization shown in Table 1. The EUR per km values have subsequently been used to analyze the entire TCO of the vehicles.

**Results and Discussion**

In a first step total costs of ownership of the selected drivetrain options have been calculated for the basic year 2010 (assuming a typical holding period of 4 years and an average yearly driving distance of 10,000 km). The cost break-down for a midsize conventional car with a gasoline engine versus a battery electric vehicle with 150 km electrical range is depicted in Figure 3. This comparison shows a significantly higher purchase price for the BEV, which is mainly driven by the expensive traction battery accounting for more than half of total production cost. On the other side operating costs are lower in all dimensions. Especially BEV energy cost make up only 30% of the ICE fuel cost. Furthermore full electric vehicles need less service and maintenance, e.g. no motor oil change and less break wear due to energy recuperation. Additionally, zero-emission vehicles benefit from the vehicle tax exemption and are not required to pass a regular exhaust inspection. However, this only partly sets off their production cost disadvantage compared to cars with conventional gasoline engines. The TCO gap between BEV and ICE exceeds EUR 20,000 for 2010 (neglecting the fact that at this point in time almost no full electric car has benn available in the market).

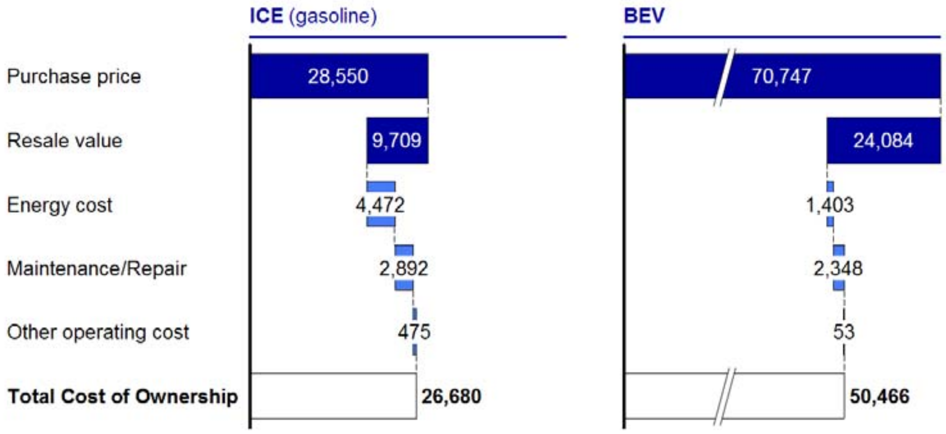


**Figure 3:** Cost break down for a conventional car (ICE) vs. full electric vehicle (BEV) in the reference year 2010 (Assuming 10,000 km annual mileage, 4 years holding period) [Source: DLR analysis]

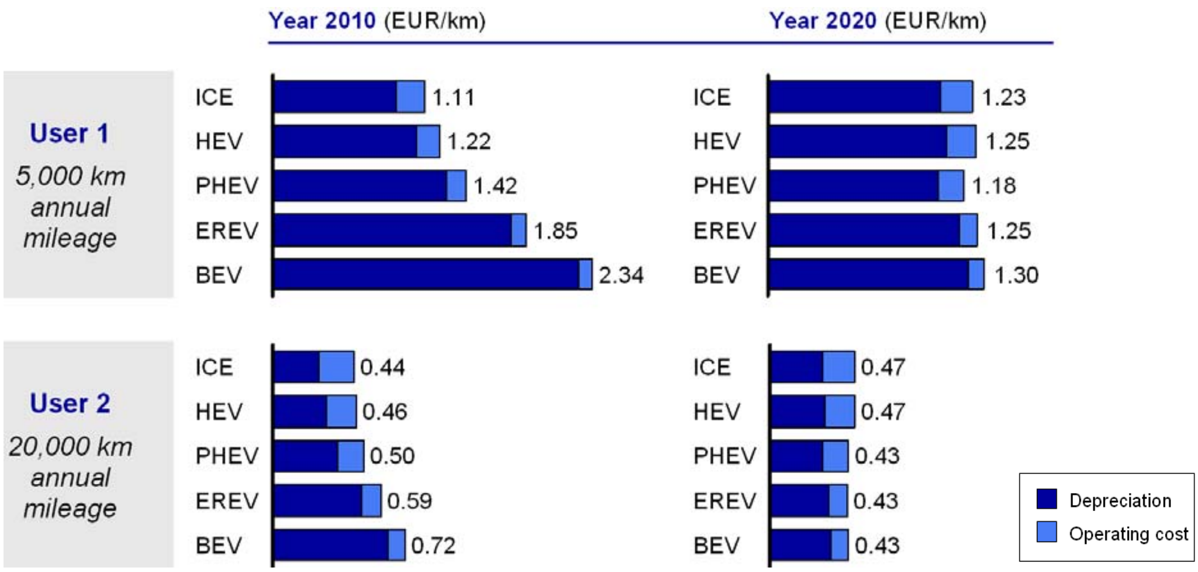


**Figure 4:** Total cost of ownership for different users in 2010 and 2020 (holding period 4 years) [Source: DLR analysis]

When comparing the TCOs of different powertrain concepts on a EUR per km basis over 4 years (see Figure 4), the cost clearly increase with higher degree of electrification in 2010. This is mainly driven by the growing battery size (from 2 kWh in the HEV to 30 kWh in the BEV), which is the most costly component of any EV drivetrain. With technological improvements and increasing economies of scale the production cost of electrified powertrain components will decline over time, which makes EVs more and more cost competitive. (For examples BEV production cost will decrease by 6% on annual average from 2010 to 2020.) This holds especially true for users with high annual mileages, who can benefit from the low running cost of EVs. According to the analysis in Figure 4 in 2020 the PHEV, EREV and BEV will be equally cost-efficient for *user 2* with an annual driving range of 20,000 km.

In next step the annual mileage is varied continuously from 5,000 km to 50,000 km and the resulting TCOs are plotted in a chart for the year 2014 (see Figure 5). This break-even analysis indicates the driving distance, after which the higher initial purchase prices of the different alternative powertrains are compensated by their lower operating costs. At the bottom of the chart is indicated which powertrain concept is cost-optimal for which driving range. The analysis shows that in near future the acquisition of hybrid cars will start to pay off for users with mileage above 24,000 km per year.

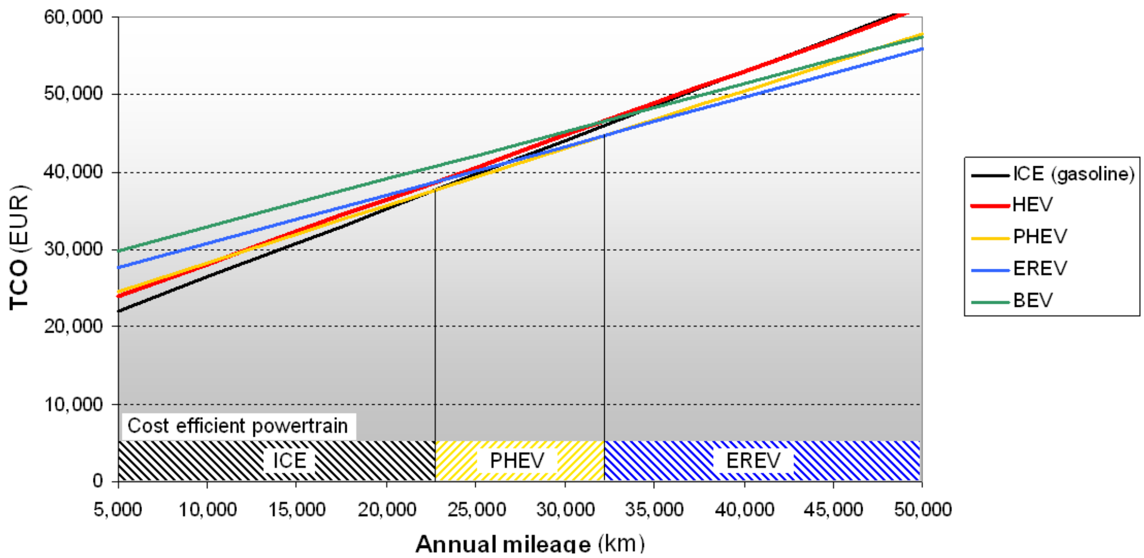


**Figure 5:** Break-even analysis for different powertrain technologies in 2014
[Source: DLR-analysis]

In a second step this analysis has been repeated for each year from 2010 to 2020 for annual mileages between 5,000 and 50,000 km. The results are summarized in Figure 6, which highlights the most cost efficient drivetrain architecture as a function of the distance a user expects to drive per year. In addition, the distribution of annual mileages in Germany according to MiD data is indicated in the lower part of the figure to show the customer potential for each category.[12] The results indicate that we will see an increasing competition between conventional cars and hybrid electric vehicles over the next years. In particular, hybrids with an external charging unit will be attractive, since they combine the energy efficiency of electric driving with the unlimited range of conventional cars. As electric motors are more energy efficient than combustion engines, the share of electric driving should be higher the more a car is used to minimize overall cost. Generally speaking, the higher the annual mileage, the higher the cost efficient battery size. According to this analysis in 2020 the EREV with a 15 kWh battery, which enables up to 70 km fully electric driving, will be the preferred option for drivers with more than 20,000 km a year, because the significantly reduced energy consumption overcompensates the additional one-time cost for a larger battery. For annual mileages smaller than 20,000 km the PHEV with 5 kWh battery size will be the cost optimal choice.

From a pure cost perspective full electric vehicle (BEV) are beneficial for high road performance, because they have the lowest operating cost of all assessed concepts. However, their limited driving range and long charging time will not allow realizing large mileages in most use cases. So over the next decade BEVs will only be interesting for niche markets (e.g. car sharing within cities) or for customer with great willingness to pay for zero emission driving.

In the long run also fuel cell vehicles (FCV), which have not been assessed in this paper, have a great potential, because they promise longer driving ranges than battery electric vehicle at comparable energy cost and relatively short refill times of their hydrogen storage. Prerequisite for the market acceptance of hydrogen powered cars is a sufficient $H_2$ infrastructure and a significant decrease in production cost of fuel cells. However, FCVs should be included in future cost analyses.

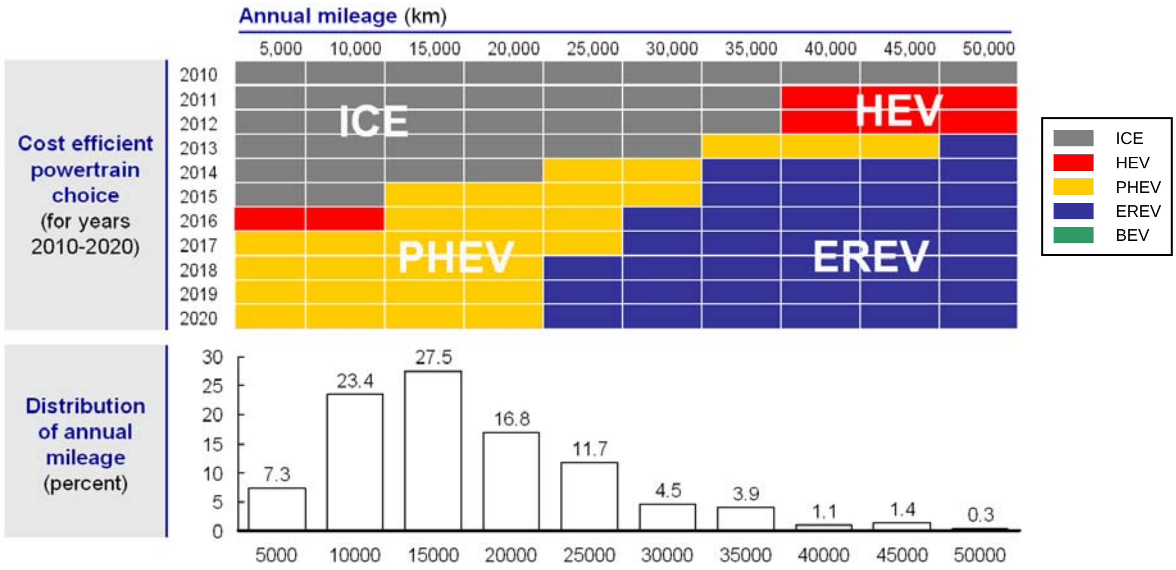


**Figure 6:** Analysis of cost-optimal powertrain choice for users with different annual mileages from 2010-2020 versus distribution of annual mileages driven by German passenger cars
[Source: DLR-analysis, MiD 2008 data]

**Conclusion**

The assessment shows that the current TCO gaps for alternative drivetrains will increasingly converge by 2020. However, depending on the specific driving characteristics different powertrain concepts will fit best to different users. This implies that there will not be one dominant powertrain design over the next decade. Hence, OEMs have to monitor closely the future technological development and regularly review their powertrain portfolio. In this context the paper provides a methodology and fact-basis to assess the cost competitiveness of alternative powertrains.

Finally, the key insights of this analysis should be summarized:

- The TCOs of different powertrain concepts are converging over time, which will intensify the competition between alternative propulsion technologies.
- The cost-efficiency of powertrains depends highly on the mileage a user expects to drive per year and the point in time of its purchase.
- From a cost perspective, cars with electrified drivetrains should be first choice for people driving high mileages in the future. However, the limited electrical range of full electric cars (BEV) will restrict their market success for the foreseeable future to few selected use cases.
- Hence, in the mid-run hybrid electric vehicle (especially PHEV and EREV with external charging) will be an attractive option due to their low running cost in combination with unlimited driving range.
- Due to the great number of influencing factors decision making becomes more complex.
- In conclusion, this dynamic market environment will lead to a variety of different drivetrain architectures, which in turn lead to increased risks for automotive OEMs and suppliers.

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