Evaluation of a 2-speed Transmission on Electric Vehicle's Energy Consumption

P. Spanoudakis, N. C. Tsourveloudis, G. Koumartzakis, A. Krahtoudis, T. Karpouzis, I. Tsinaris
School of Production Engineering & Management
Technical University of Crete
Chania, Greece
hroniss@dpem.tuc.gr, nikost@dpem.tuc.gr

***Abstract*— In order to explore the impact of transmission use on the energy/fuel consumption of zero emission vehicles, a 2-speed gearbox was developed and tested. The gearbox is installed on a hydrogen fuel cell powered urban vehicle, the ER14, a prototype designed by the TUC Eco Racing team at the Technical University of Crete. In this work the ER14 is used as a testbed vehicle so as to measure and evaluate fuel consumption with and without gear changing. Actual road tests were conducted and experimental results are presented, showing reduction of electric vehicle energy consumption with the use of the gearbox.**

Keywords—Electric vehicle, transmission, fuel cell, powertrain, gear change, fuel consumption.

I. INTRODUCTION

While many vehicles with internal combustion (IC) engine meet low emissions standards, these will give way to new, stricter government regulations in the very near future. With limited room for improvement, and given the natural limits of fossil fuels, automobile manufacturers have begun full-scale development of alternative power vehicles. Thus, other vehicle types are researched and produced towards zero emissions goal, like electric and fuel cell powered vehicles. At the same time, efficiency of every engine and power transmission components are explored in order to achieve lower fuel consumption and higher autonomy. Nowadays much focus has been given by the automotive industry on new or optimized powertrain systems that can significantly improve fuel consumption especially in IC engine vehicles. But since hybrid, fuel cell and electric vehicles are becoming more feasible and promising, such fuel efficient powertrain systems are researched for hybrid/electric cars too [1].

Most current production vehicles use either conventional Manual Transmissions (MTs) with discrete gear ratios or Automatic Transmissions (ATs) configured with planetary gear sets that use integral clutches and bands to change gear ratios. MTs use five to seven discrete gear ratios while ATs have four or five. Alternatively, Continuously Variable Transmissions (CVTs) introduced an infinite gear ratio variation instead of the previously mentioned discrete gear ratio transmissions. Their efficiency, torque transfer and thus application and use vary [2, 3, 4, 5].

Nowadays, Electric Vehicles (EVs) are equipped with a single-speed gearbox in order to reduce cost, volumes, losses and drivetrain mass [5]. But, gearbox use can be a solution in order to meet the design requirements of vehicle acceleration and maximum speed, where high-performance traction motor and batteries are required. Thus, a 2-speed or even an n-speed gearbox may be installed to increase the wheel torque at low vehicle velocity and extend the maximum vehicle speed. An ongoing research of gearbox or alternative transmissions use on electric vehicles (EVs) is found in literature [6, 7, 8, 9, 10], including simulation based comparisons using 2-speed versus single speed gearbox use [15, 16]. Finally, some concept gearbox prototypes targeting mostly EVs use, are already presented in the market, such as those by Vocis/Oerlikon Graziano and Antonov [12, 13]. The target of course is higher EVs' range.

It should be mentioned that other technologies regarding reduction of energy consumption are also found in literature, mainly addressing topics such as [17]: 1)Flywheel energy storage, 2)Regenerative braking, 3)Energy management systems, 4)Thermoelectric generators, 5)Energy conserving options for electrical accessories, and other possible solutions. Even though every one of the above can achieve specific benefits, no direct comparison between these techniques has been found so far. Nevertheless, our research team has verified through on road tests that alternative transmissions provide energy reduction and thus focuses on this topic.

To the best of our knowledge, no real comparison has been made, including real on road tests, in order to identify if a gearbox use can provide a feasible solution towards reduced energy consumption. The research presented here, covers the use of a prototype gearbox transmission on an urban electric vehicle, presenting real on road tests and comparisons that may provide valuable insights on the topic.

II. EXPERIMENTAL SET-UP

A. Testbed Vehicle Specifications

In order to evaluate the use of the transmission system through on road experimental testing, the prototype urban vehicle ER14 was used (Fig. 1). It is a one seat, ultra light vehicle for urban environments, developed by the Technical University of Crete Eco Racing team (TUCER) [11]. An

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electric motor powered from a H_2 fuel cell, make up the vehicle's energy system. The basic powertrain consists of a one-stage geared transmission with ratio 1:10, placed between the electric motor and the wheel. Testbed technical specifications are presented at Table 1. The vehicle weight (excluding the driver) is measured at 83kg with one-stage transmission, while with a gearbox installed it is found 85Kg.

B. *Powertrain Specifications*

The standard testbed vehicle powertrain configuration consists of: 1) a Hydrogen Fuel Cell, 2) an electric motor and 3) a one stage gear transmission with ratio 10:1, which is as shown in Fig. 2 but without the gearbox. The Fuel Cell uses hydrogen (200bar bottle) in order to power the electric motor, which drives the vehicle. The one stage gear transmission is placed between the motor and the wheel in order to provide needed torque and rpm.

When the 2-speed change gearbox is installed, a two-stage transmission system occurs, while the rest of the drivetrain remains unchanged (Fig. 2). The second stage (transmission) is kept exactly the same providing a 10:1 ratio, while the first stage (gearbox) provides a gear change with ratios 1.4:1 and 1:1 respectively. Thus, the final transmission ratios are 14:1 (1^{st} gear) and 10:1 (2^{nd} gear), corresponding to launch and cruise vehicle driving modes.

Fig. 1. The prototype testbed vehicle ER14.

TABLE I. TESTBED VEHICLE SPECIFICATIONS

Chassis	*Aluminum alloy*
Body	*Carbon fiber*
Motor	*Brushless electric motor*
Max Motor Torque	*4 Nm*
Max Motor RPM	*4000 RPM*
Power Source	*H_2 fuel cell, 1.2KW*
Dimensions	*2.5x1.25x1m (LxWxH)*
Weight	*83Kg/85Kg(with gearbox)*
Max Vehicle Speed	*37 Km/h*

The first stage of the transmission presented, is a prototype build to be installed on the specific testbed vehicle (ER14). It is a low weight (aluminum – 1.8Kg) gearbox, using two gear sets placed on two axles (Fig. 3). The gears placed on the first axle (driving axle) turned by the electric motor are firmly attached on it, while the gears placed on the second axle (driven axle) turn freely on bearings that are fixed on the axle. A simple synchronizing mechanism is used to manually change from one gear set (1^{st} gear) to the other (2^{nd} gear). When no gear is selected, the driven axle does not transfer any power to the second transmission stage and to the wheel. If either of the gears is selected, the power is transferred with the selected ratio to the second stage of the transmission. Fig. 4 shows the custom build gearbox as installed on the testbed vehicle.

As already mentioned, the use of the gearbox targets lower energy consumption during launch but also at vehicle cruising speed (25km/h). This is achieved using the selected gear ratios of 1.4:1 and 1:1, which according to theoretical calculations, provide lower torque demand at launch and almost equal during cruising speeds (Fig. 5). For these calculations gear change is performed at 11km/h and a perfect shift is assumed, meaning no power losses are accounted.

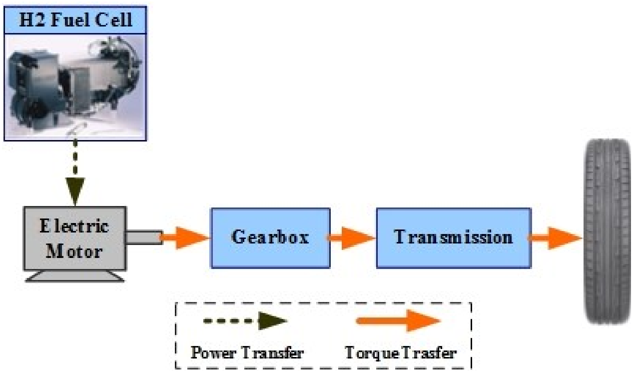

Fig. 2. Testbed vehicle drivetrain configuration with installed gearbox.

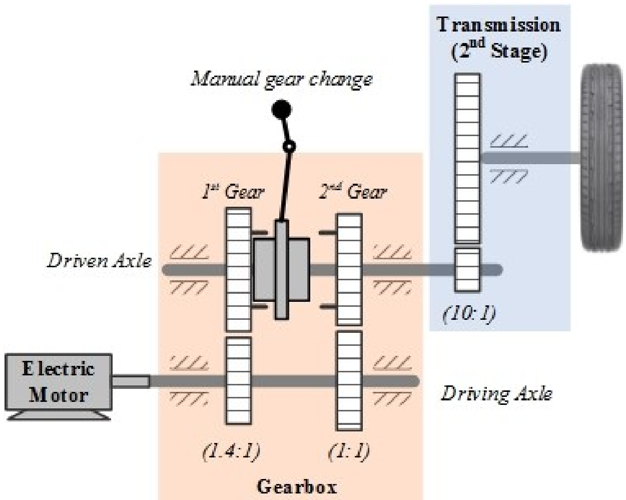

Fig. 3. Detailed drawing of 1^{st} and 2^{nd} transmission stages, showing gear change and corresponding ratios.

C. On Road Tests Setup

An open test track at the University campus is used for the tests, where one full lap corresponds to 240m (Fig. 6). The test case procedure is to complete two full laps corresponding to 480m distance. The tests were conducted firstly with one-stage transmission, measuring: *time, distance, vehicle velocity, power and hydrogen consumption*. Then, the gearbox was installed and the same tests were conducted again in order to compare fuel consumption data. Gear change was performed at different speeds (8, 11, 14Km/h) in order to investigate how this effects vehicle's fuel consumption. At both cases full throttle was used.

It must be stated that the testbed vehicle is developed for competition purposes, where an average speed of 25Km/h is the target. That is the reason why this specific speed is used throughout the tests.

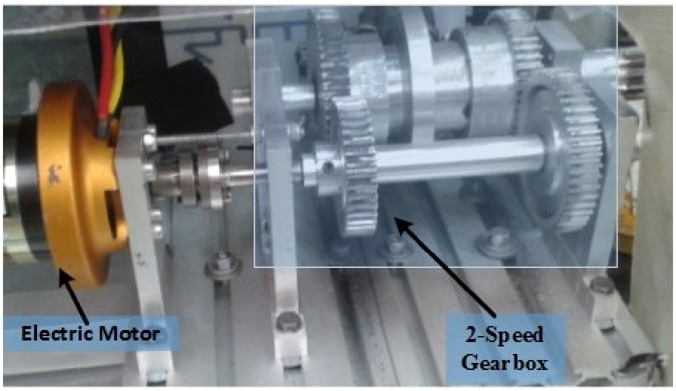

Fig. 4. A view of the custom build prototype 2-speed gearbox, installed on the testbed vehicle.

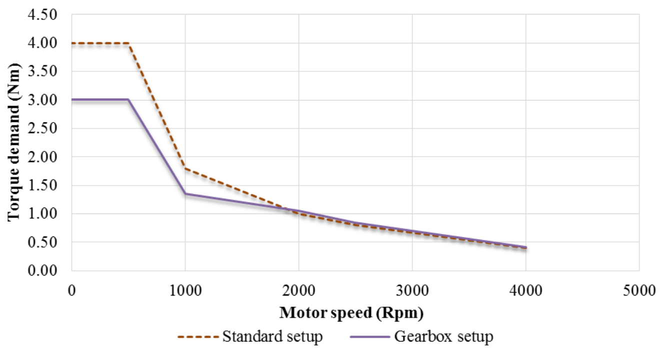

Fig. 5. Torque demand versus motor speed using the standard powertrain setup and gearbox setup for the ER14 vehicle.

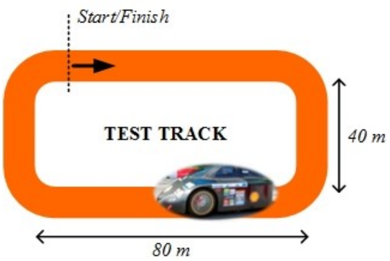

Fig. 6. Test track specifications, used for on road tests.

III. RESULTS AND COMPARISONS

According to already mentioned experimental setup, series of on road experiments are conducted to evaluate the energy consumption with and without the use of a gearbox. The collected results are based on the data recorded for every lap covered on the test track and are presented at the following figures, showing power demand (Watt) versus sampling time. Mean power and total hydrogen consumption are also recorded and presented, for adequate results evaluation. Hydrogen consumption is of major importance since it becomes the key evaluating parameter when speaking of a Fuel Cell Electric Vehicle. It should be noted though, that H_2 consumption is almost proportional to power demand, following a curve according to Fuel Cell specifications [14]. Hence, both readings should change seamlessly and provide vehicle energy demand changes. Time shown at graphs x-axis, corresponds to data recording sampling rate, which is twice per second. Experimental results are presented in two categories: *Standard Powertrain setup* and *Gearbox setup,* respectively.

A. Standard powertrain setup

At this test case the standard ER14 powertrain configuration is used. Two laps are completed at the test track and the power demand is presented at Fig. 7. As shown, power is minimized only at the corners, while power demand exceeds 350W at the rest of the track. The H_2 consumption was measured at **4.42lt/min** and mean power demand was calculated at **216.34W**. As mentioned, the vehicle is accelerated at full throttle, which corresponds to higher energy consumption but minimizes driver's influence on results. For that reason the test is performed again following an economy driving strategy throughout the laps (Fig. 8). The velocity limit of 25 Km/h is again reached at every lap, but with slower acceleration during launch and corners exit. H_2 consumption was measured at **0.76 lt/min** and mean power was calculated at **148.40W**. Results clearly show a dramatic drop on energy consumption, when following a more economy driving strategy. Moreover, vehicle launch (0-60sec) presents the most significant power demand drop (nearly 50%).

B. Gearbox setup

The two-speed gearbox is installed on the vehicle and 2-lap tests are performed again following exactly the same procedure. The main differentiation is the gear change phase which alters vehicle performance. For evaluation purposes gear change is done at three different vehicle speeds (8, 11, 14Km/h) during launch. As seen at the first test case, less energy during launch and moreover better vehicle acceleration can provide lower energy consumption. Since the main objective is to evaluate how gear change can affect fuel consumption, this is performed at the aforementioned vehicle speeds (Fig. 9, 10, 11, 12). Mean power demand and H_2 consumption at different gear change speeds are presented at Table II. Lowest energy consumption is found at 11km/h, where both evaluating parameters match to this result (H_2 consumption: **4.27lt/min**, mean power demand: **198.64W**).

Results also indicate more evaluation info to be noted, which are:

1) When gear change is conducted at higher speeds, the power demand is higher (up to 20-30 units of sampling time), which is expected.

2) After the gear change, power demand increases since the vehicle accelerates to reach 25km/h. Neverhteless, at 11km/h the power curve is smoother resulting to lower power values during the first lap. That is evaluated as the most imporant factor for the lowest fuel consumption among these tests.

3) Second lap power curves are almost identical at all tests, since vehicle is moving with the same gear ratio. Thus, no real difference can be found in energy consumption (Fig. 10).

TABLE II. ON ROAD TESTS WITH GEAR CHANGE AT DIFFERENT VEHICLE SPEEDS

Gear Change Speed (Km/h)	Mean Power Demand (W)	H_2 (lt)
8	202.53	4.29
11	**198.64**	**4.27**
14	231.92	4.69

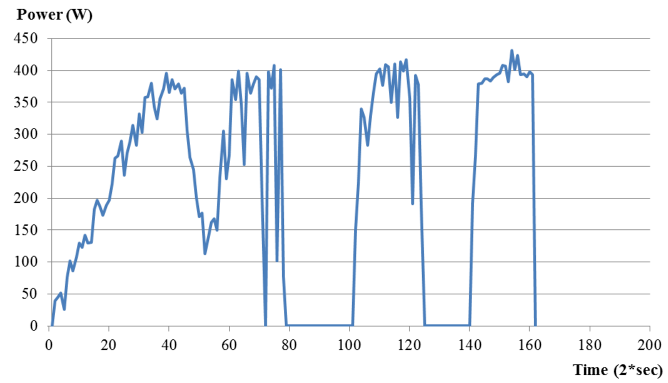

Fig. 7. Two lap test with standard powertrain setup and full throttle.

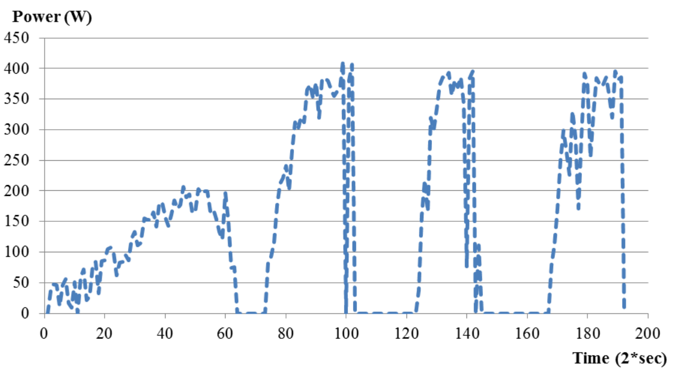

Fig. 8. Two lap test with standard powertrain setup and economy driving strategy.

C. Results Evaluation

So far, results were evaluated separately, regarding no gearbox and with gearbox tests respectively. Since the main scope of this work is to evaluate the use of a gearbox on an electric vehicle, the best of this results (regarding fuel consumption) are chosen and are directly compared hereafter.

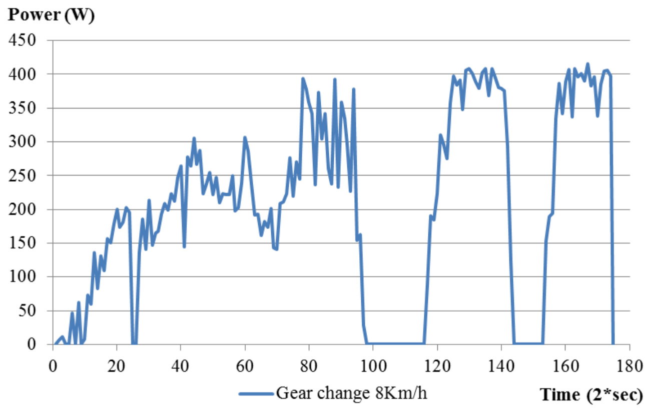

Fig. 9. Two lap test with gearbox setup and gear change at 8km/h.

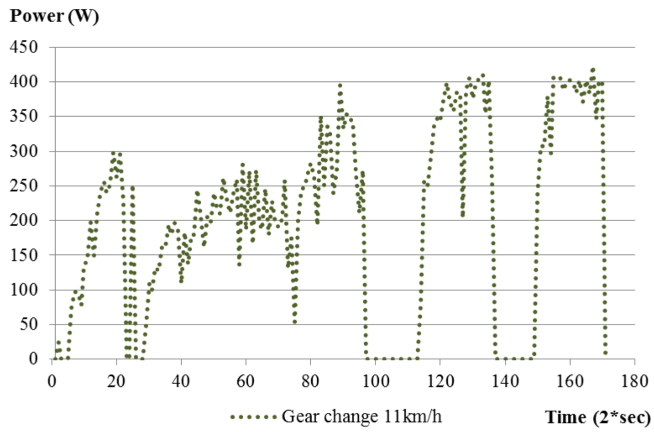

Fig. 10. Two lap test with gearbox setup and gear change at 11km/h.

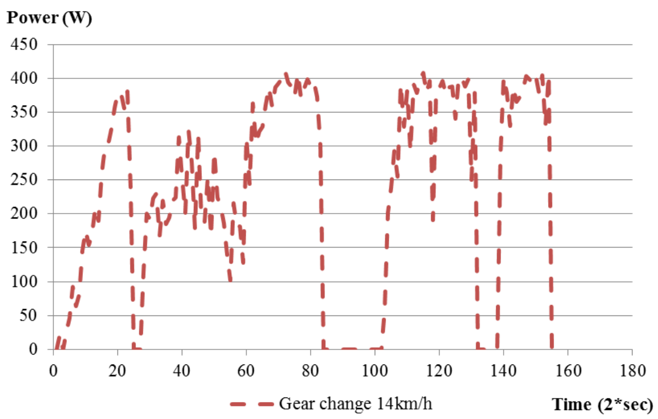

Fig. 11. Two lap test with gearbox setup and gear change at 14km/h.

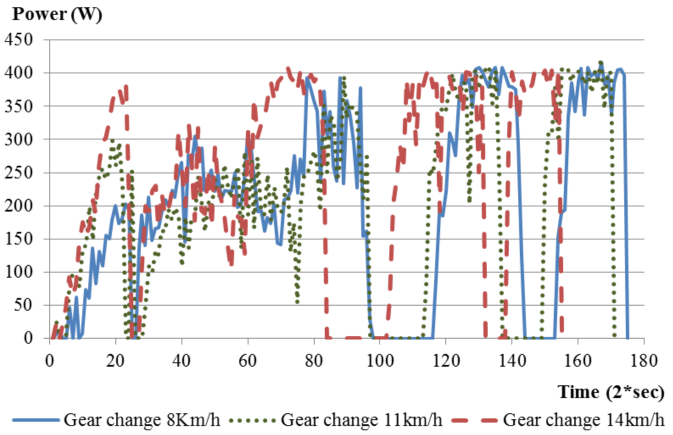

Fig. 12. Two lap test with gearbox setup and gear change at various vehicle speeds (8, 11, 14km/h).

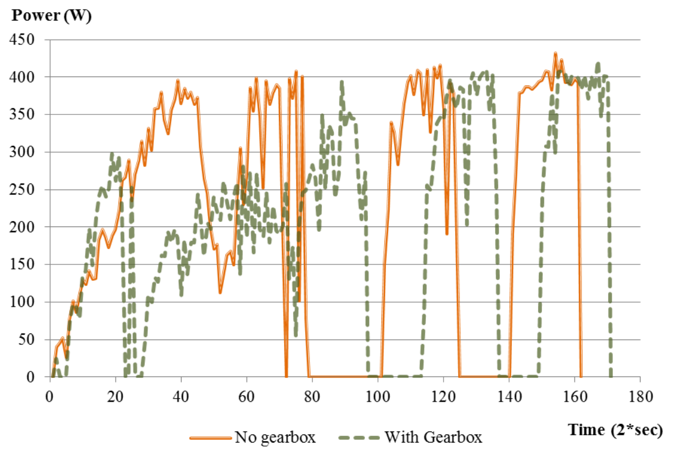

Fig. 13. Final power demand comparison of best gearbox setup (11 km/h) versus standard powertrain setup, in two lap tests.

The most important outcome is that on road tests validate that fuel consumption can be reduced using a fine tuned gearbox up to **3.4%** (*No gearbox: 4.42lt* H_2*, With gearbox: 4.27lt* H_2). Even though this percentage seems low, it must be noted that tests conducted included just one launch during the laps. If those tests are performed in a city circle where often stop & go are necessary, fuel consumption will be further reduced. This specific argument can be validated using a direct comparison of the power demand curves between the two tests (Fig. 13). As seen, during launch the vehicle with gearbox performs much smoother, resulting to lower power values. Moreover, since a prototype gearbox was used, there is plenty of improvement that can be done regarding its efficiency, which will reflect to additional fuel consumption drop.

Another important evaluation outcome is that gear change speed has major effect on fuel consumption. Thus, as already done in vehicles using ICE (Internal Combustion Engines), a driver can achieve to use his vehicle economically using indicators of best gear change speed. That is why fine tuned is stated above, since if the gear change occurs at certain speeds (14Km/h) it can result even to higher consumption.

Finally, concerning vehicle performance and driving, there was no problem indicated during tests (power drop, lack of acceleration) that would trouble in any way the driver or raise usability concerns.

IV. CONCLUSION

The evaluation of gearbox use in electric vehicles is presented. A prototype gearbox was designed, developed and tested on road, in order to explore the performance of a two-gear change capability on zero emission urban vehicles. A prototype hydrogen fuel cell powered urban vehicle was used as a testbed for on road tests. Experimental results were presented for *Standard Powertrain setup* and *Gearbox setup*. At Standard powertrain setup a one-stage transmission was used, while at Gearbox setup the prototype gearbox was installed and gear change was performed at different speeds (8, 11, 14Km/h). It was shown that gearbox use in electric vehicles can provide lower energy consumption and higher autonomy, especially in urban environments.

Experimental results validated that fuel consumption can be reduced using a fine tuned gearbox up to **3.4%.** Even though this percentage seems low, it should be noted that tests conducted included just one launch per test. If those tests are performed in a city circle where often stop & go are necessary, a greater reduce of fuel consumption should be expected. Moreover, since a prototype gearbox was used, there is plenty of improvement that can be done regarding its efficiency, which will reflect to additional fuel consumption drop. Another important evaluation outcome was that gear change speed has major effect on fuel consumption. Thus future work could focus on gearbox use with optimal gear change control.

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