Abstract

Electric Vehicles are gaining popularity due to their low carbon footprint and ease of integration with renewable energy. They are an important element in the smart grid ecosystem. Increasing the driving range of storage driven electric vehicles is the biggest challenge facing the light weight electric vehicle industry. A literature review has been performed to identify various techniques to improve the driving range. Various methods of driving range improvement such as new storage topologies, switching techniques, motor configurations are studied. A new quantitative measure called as impact factor has been derived to see the effect of each technique on the driving range. Impact factor for different methods has been calculated. It is shown that, increasing the storage capacity has the highest impact factor on the driving range.

Keywords: Electric vehicle; Driving range; Converter technology

1. Introduction

The Electric vehicles have been around since middle of 19th century [1,2]. However, the electricity was primarily generated using coal and other fossil fuels. Driving electric vehicles meant double energy conversion, first one was from fossil fuel to electric energy and the second one was from electric energy to kinetic energy. This made it economically expensive solution. In addition to that, ample oil reserves were discovered and gasoline powered vehicles became the most cost and energy efficient means of transport. Now that the world is facing severe shortages in the gasoline and rising prices, also giving power to the electric vehicles, storage made them an important element in the smart grid.

There are many different terminologies for the electric vehicles based on their utilization of electricity. Grid connected electric vehicles are the ones which use the electricity from overhead or underground cables. Typically, electric trains and trolley buses are developed using this concept. Battery based electric vehicles have rechargeable batteries on the vehicles. The vehicle uses the energy from the battery. Battery needs to be charged after the drive. The Hybrid Electric Vehicles (HEV) use battery and conventional fuels to run the vehicles. The battery in the hybrid electric vehicles do not need separate charging as it gets charged from the vehicle stoppages, also known as regenerative braking. The Plugin Electric vehicles (PEV) use batteries which can be charged from a regular electricity power outlet in a house or any commercial place. The plug in hybrid electric vehicle use similar concept for a hybrid electric vehicle. Since large scale grid connected electric vehicles like trains and trolley buses require a lot of infrastructure, most of the electric vehicles research focus is shifted towards either entire storage based electric vehicles or hybrid electric vehicles which have ability to run on electricity and conventional fuels [3].

Depending on the type of the electric vehicle, various technology areas are being worked upon. One of the technology areas in the electric vehicles is development of newer control architectures. Researchers are working on many different electrical topologies and control strategies to improve the overall performance of the electric vehicles. These topologies are primarily for driving the electric motor [4,5]. Development of battery charging circuits is another research area. Various battery chargers such as on board, offboard and wireless chargers are being developed [6,7,8]. Grid stability and electrical load management issues are also studied extensively in connection with the electric vehicles [9,10]. Using the battery
in electric vehicles, excess grid energy from the renewables can be stored and also the same battery can be used by the grid operator to help the grid recover from short term voltage sags and dips caused by load changes. Despite of this academic level research on various aspects, the entire growth in the storage device driven electric vehicle industry in the commercial segment is focused around a single problem. This problem is to extend its driving distance with longer charge durations.

The purpose of this paper is to present a literature review of the various methods researchers have developed to improve the driving range. For the purpose of this paper, the discussion has been focused around light and medium size and weight vehicles, primarily electric cars and buses. To improve the driving range of the vehicle, it is necessary to understand its basic building blocks and its connection to the driving range. Hence, section 2 discusses basic structure of the electric vehicle. Section 3 presents various methods to improve the driving range. A comparison of methods and their impact on the driving range is performed in section 4 and section 5 concludes the paper.

2. Structure of Electric Vehicle

All the electric vehicles have four main building blocks. First one is the battery to generate a DC voltage, second one is a DC to AC converter to convert the DC voltage to high frequency AC voltage, third one is the AC motor coupled to the drive train and fourth one is the battery charger circuit to charge the batteries. Sometimes, an additional DC to DC converter is also required to step up the low voltage from the batteries. Fig. 1 shows a block diagram of the electric vehicle. The details of each building block are discussed later.

*) Battery

The battery specifications for the electric vehicles differ for different types of electric vehicles. Most of the cars use lithium ion batteries with 370V as nominal DC voltage. The battery capacity ranges from 20kWh to 100kWH. Higher is the battery capacity, more is the driving range of the vehicle. The driving range for the current electric vehicles ranges from 60 miles per charge to 380 miles per charge.

*) DC to AC Converter

DC to AC converts the DC voltage to an AC voltage with varying frequency and voltage. This enables smooth speed control of the vehicle. The input DC voltage to this converter has a nominal operating range of 280V to 360V. This voltage is generated either by directly using high voltage batteries or a separate step up converter along with the low voltage batteries.

*) Motor

Three types of motors are used for electric vehicles. They are brushless permanent magnet synchronous motors, AC induction motors and switched reluctance motors. AC induction motors are more popular for cars for various reasons [11]. They have ease of manufacturing and lower cost. They also have good overall efficiency over the entire load and speed operating range. They also need less maintenance due to lack of brushes. The permanent magnet motors have high starting torque and have high peak efficiency. They are used in medium weight or traction applications. Switched reluctance motors are the recent additions to the electric vehicle. They do not need permanent magnets on the rotor and have high efficiency and high torque.

*) Battery chargers

Most of the electric vehicles are supplied with on board chargers. They are categorized in to level 1 or level 2 chargers [12]. They can take input from the AC voltage of the residential electricity outlet and convert the AC voltage in to a DC voltage to charge the battery. They are slow chargers but are most popular due to direct AC outlet connections. Level 1 chargers take input from 110V AC and level 2 chargers take input from 220V AC. To have fast charging abilities, level 3 and level 4 chargers were developed. They are high voltage DC charges which by pass the on board chargers completely. Level 3 chargers have the ability to provide up to 50kW of power per vehicle and level 4 chargers have the ability to provide 120kW of power per vehicle.

3. Improving Driving Range of Vehicle

The power required by any electric vehicle at the wheel consists of four main components [13,14,15]. First one is the base electric load such as heater, air conditioning, music system etc. Second one is the power required to overcome aerodynamic drag and air resistance to the vehicle. Third component is the power required to overcome rolling resistance by the wheels. Fourth one is the power required to work against gravity during upwards and downwards slopes of the road and the fifth one is power required for overcoming inertia of the vehicle. The total power is given by Eq. (1).

\[ P_w = P_b + P_wl + P_d + P_g + P_{acc} \]  \hspace{1cm} (1)

\[ P_a = \frac{1}{2} \rho C_d A_f V^3 + C_r M g V + M_{eff} \frac{dV}{dt} + P_b \]  \hspace{1cm} (2)

where, \( P_b \) is the base electric load, \( \rho \) is the density of the air, \( C_d \) is the coefficient of the drag, \( A_f \) is the frontal area of the vehicle, \( V \) is the vehicle speed, \( M \) is the mass of the vehicle, \( g \) is the acceleration due to gravity, \( C_r \) is the co-efficient of rolling resistance [14,15].

\[ M_{eff} = M + M_{f} \approx 1.1M \]  \hspace{1cm} (3)

Average energy \( E_w \) over one driving cycle is given by:

\[ E_w = \int_0^t P_w \, dt \]  \hspace{1cm} (4)

where \( t \) is the total driving time and the driving range \( R \) is given by:

\[ R = \frac{E_w}{E_{wv}} \]  \hspace{1cm} (5)
where \( E_b \) is the energy in the battery, \( n \) is the efficiency of the entire traction system, \( ΔSOC \) is the window of battery state of charge and \( E_{iut} \) is the initial battery energy and \( n \) is further given by:

\[
\eta = \eta_{\text{converter}} \times \eta_{\text{motor}} \times \eta_{\text{drive\-main}}
\]

Driving range of any electric vehicle can be improved by improving any of its building blocks. Following sections discuss various methods researchers have been used to improve the driving range.

### 3.1. Improved Storage Technology

Storage technology has been evolving rapidly. Lithium ion batteries are most popular choice for electric vehicles due to their high capacity and weight. Many materials are being used for cathode, anode and electrolytes for increasing the efficiency and overall battery performance. Some of the common materials for cathode are lithium manganese oxide (LMO) or lithium iron phosphate (LFP). Lithium iron phosphate has high current capability with very good thermal performance and less aging. They also easily replace lead acid by stacking in multiples of 4 cells. Lithium Nickel Cobalt Manganese oxide batteries have high energy density and good thermal characteristics. They are the most popular batteries for electric bikes. Besides researching on using different ions of Lithium, completely different materials are being used for packing very high energy density. One such alternative is Lithium sulfur battery. It has theoretically, 3 to 4 times the energy density than the conventional lithium ion battery. Lithium air battery is another promising alternative where the battery capacity is increased by 5 to 10 times with very light weight.

Driving range can also be increased by adding different storage materials on top of batteries. This system of combining multiple types storage devices is known as Hybrid Energy Storage System (HESS). One option in this system is using ultracapacitors or supercapacitors in parallel with batteries. Ultra-capacitors can store the energy for a short time but have infinite number of charge and discharge cycles theoretically. The power electronics converters can be designed to take input from ultracapacitors during fast high energy bursts and keep the batteries for steady state operation. Figure 2 shows various ways in which ultracapacitor can be connected in parallel with the battery. Fig. 2(a) shows a direct parallel connection of the battery with the ultracapacitor. Fig. 2(b) shows a bi-directional DC to DC converter balancing the power flow between battery and ultracapacitor. Fig. 2(c) shows two separate inputs from the ultracapacitor and battery to the DC to DC converter. Fig. 2(d) shows ultracapacitor bypassing the DC to DC converter to have high efficiency of power processing.

Fig. 3 shows another novel approach of combining ultracapacitors and battery. This concept is based on a bi-directional DC to DC converter with the ultracapacitor connected in series with the output of the converter. The bi-directional DC to DC converter shares the power between ultra-capacitor and battery. Very high efficiency, optimum battery capacity usage and complete control over ultracapacitor current are achieved by operating the converter in different modes in different operating conditions of the vehicle. Figs. 3(b), (c) and (d) demonstrate all the operating modes.

Fuel cells are another storage option increasingly being considered for electric vehicles. Fuel cells have high energy density, many times higher than lithium ion batteries but they have a poor response time. Ultracapacitors have a fast response time but very low energy density. Batteries can provide high continuous power. Combining the benefits of all the three storage technologies, overall vehicle efficiency can be significantly improved. Fig. 4 shows a block diagram of the system with all the three storage technologies. In this block diagram although three separate DC to DC converters are shown to process the power from three storage mediums, configurations similar to those shown in Fig. 2 and Fig. 3 can be derived for higher efficiency.

### 3.2. Improving the Converter Technology

As discussed in the earlier sections, three types of motors are considered for electric vehicles. First one is the brushless DC motor, AC induction motor and switched reluctance motor. Researchers have been working on developing different converter topologies for each type of motor. Fig. 5 shows two commonly used power converter topologies.

To improve the driving range, the power converter driving the motor needs to be very efficient. Any converter loss consists of two components: First one is switching loss and the second one is conduction loss. The switching loss is given by Eq. (8):

\[
\text{Switching loss} = \text{DC link voltage} \times \text{average switch current} \times (T_{on}+T_{off}) \times \text{switching frequency}
\]

where \( T_{on} \) and \( T_{off} \) are switch on and off times in the converter.

The conduction loss is given by the Eq. (9):

\[
\text{Conduction loss} = \text{switch on storage voltage} \times \text{average switch current} \times \text{duty cycle}
\]

To reduce these losses various techniques are being worked upon. One of the techniques used in [4] is to design optimized gate driver circuit. In this method, authors have designed a new gate driver circuit which improves the turn on and turn off speeds of the power devices. This results in reduction in switching times for the MOSFETs and hence lower switching losses. The overall efficiency of the converter is improved. Another technique for the loss reduction is using either of the two strategies known as Maximum torque for a given current (MTPC) and Maximum Efficiency (ME) for a given current.
current and speed and also the maximum flux. These losses vary with different operating points. During low speed of operation, the losses are primarily current dependent and hence the first scheme could be used to decide the operating point. During medium to high speeds, the losses are dependent on the maximal flux in the motor. In this case, a loss model based on the flux is developed and the required current value is determined by an optimization program. The control shifts the operating point from minimum current to minimum losses.

Another approach to further minimize the losses in the MTPC strategy is to use finite predictive current control. In this method, the back EMF and current are estimated from the previously stored value and hence dynamic torque of the motor is improved [5].

The efficiency of the drive circuit can also be increased by introducing different modulation techniques for the switching devices. Fig. 6(a) shows the conventional pulse width modulation technique. It is most commonly used to control the motor operation. In this modulation, at lower speed very narrow pulses are generated [27] and higher speed wide pulses are generated. This increases the AC voltage. This type of switching may not lead to optimum efficiency of the power processing. To overcome that, another technique being in use is, Pulse Amplitude Modulation (PAM). In this technique, the amplitude of the pulses is varied as against the pulse width. This modulation leads to higher efficiency in some operating modes. This modulation is shown in Fig. 6(b).

Although PAM seems to be the right approach, conventional PWM is more efficient than PAM during some parts of the operating area of the vehicle. Hence it is necessary to optimize the switch modulations over the entire operating region of the vehicle. This optimization is achieved using a chopper in front of the conventional converter circuit. The chopper varies the DC link voltage and the converter modulates the pulse widths. So, the result is quasi-PAM technique. This approach is shown in Fig. 7. In this modulation, the switch is modulated using amplitude and also pulse width [27].

Switching frequency can also be modulated to improve the converter and motor performance. Bang-Bang type of current control has been implemented in [25] to achieve this type of modulation. Fig. 8 demonstrates this type of control.

Figure 1. Block diagram of an electric vehicle

Figure 2. Hybrid energy storage using ultracapacitors (a) Ultracapacitors connected in parallel with the battery (b) DC to DC converters sharing power between battery and ultracapacitor (c) dual input DC to DC converter (d) Ultracapacitor bypassing the DC to DC converter

Figure 3. A high efficiency hybrid energy storage using ultracapacitors (a) Basic topology (b) power flow from the battery to the motor during acceleration (c) power flow during the constant speed (d) power flow during deceleration [21]

Figure 4. Hybrid energy storage using fuel cells, ultracapacitors and battery
Motor has mainly two types of losses. First one is copper loss and the second one is iron loss. The copper losses in the motor are proportional to the square of motor current as given by Eq. (10).

\[ P_{cu} = I^2 \times R \]  

(10)

where \( P_{cu} \) is the copper loss, \( I \) is the stator current and \( R \) is the winding resistance. Due to the pulse width modulating currents, the motor current has many harmonics besides the fundamental component. The effective winding resistance is different for each harmonic frequency. Many different types of PWM techniques are used to reduce the AC resistance. It is possible to control the copper losses by running the motor in loss optimization mode discussed in the previous section. The iron losses are hard to control. They include eddy current losses and the hysteresis losses and are given by [27]:

\[ P_h = k_h \times f \times B_m^\beta \]  

(11)

\[ P_e = k_e \times f^2 \times B_m^2 \]  

(12)

where \( P_h \) is the hysteresis loss, \( P_e \) is the eddy current loss, \( k_h \) and \( k_e \) are the loss coefficients, \( f \) is the frequency of the magnetic field, \( B_m \) is the maximum flux density and \( \beta \) is the Steinmetz constant. Since \( B_m \) is proportional to the voltage applied to the winding, both, hysteresis and iron losses are proportional to the voltage square and voltage to the power of \( \beta \). To reduce the iron losses in the motor, one of the options is to control the voltage at the winding terminals using techniques similar to quasi-Pulse Amplitude Modulation technique discussed in [27]. This approach gives significant efficiency improvement.

Other causes of iron losses are the high frequency harmonics of the switching currents. Multiple windings are used during different operating modes of the motor to overcome these losses in [29]. These windings can be excited dynamically by using winding changeover circuits or using multiple converter circuits. Fig. 9(b) shows two stator windings wound alternately on each slot for this purpose [29].

3.4. Using PV along with EV

PV has been used with EV using two types. First type is to charge the battery in the EV. The charger itself does not need to be part of the EV. PV can charge the batteries using a DC to DC converter. When the PV is grid connected, the battery charger can be conventional AC to DC charger and PV can generate most of the electricity. When PV is unable to charge the battery, it gets power from the grid. Second type of PV integration is on board electric charging. In this case, PV panels are installed on the body or chassis of the electric vehicle and they are used for battery charging. But, this charging can be a continuous process so that the battery does not discharge completely when the PV is present. Although the panels may be of smaller capacity, they aid in battery charging and effective driving range can be increased. In [30] a unique three port converter is proposed which seamlessly integrate PV, battery and the motor used for driving the vehicle. The energy ex-
change takes place in these three terminals without additional circuits. This saves in overall converter losses and hence the efficiency of the system is higher. Fig. 10 shows this circuit.

In [31] an on-board, PV based battery charger is used for auto-rickshaws. Auto-rickshaws are three wheeled, low speed vehicles which carry passengers in medium size cities of many of the developing countries. The on board PV battery charger trickle charges the batteries and keep them charged for a longer time. This helps in increasing the driving range significantly. Fig. 11 shows a block diagram for this system.

While integrating PV, the study has also been done to see the effectiveness of different panel technologies for improving the driving range. It was found in [13] that mono and polycrystalline silicon PV panels are very effective for use with the light weight vehicles.

3.5. Using Wind Power to Increase Driving Range

Similar to PV, wind energy can also be used to increase the driving range of the vehicle. A small wind turbine can be placed on the body of the vehicle. When the wind blows during vehicle motion, it can trickle charge the battery inside the vehicle leading to higher driving range. The wind can be used for on board charging or off board charging. There has been some research and patents on this approach. For example, in the US patent 8,098,040 B1 driving range has been increased using RAM air turbines. The energy resulting from the vehicle movement is tapped by these turbines. The turbines are coupled with a generator. When the vehicle moves, the generators charge the battery. These RAM turbines are mounted inside the vehicle. The energy received by this method can also be used in conjunction with an ultra-capacitor for quick charge and discharge cycles [32]. Fig.12 shows this method.

3.6. Contactless Power Transfer

Traditionally battery in the electric vehicle is charged by using high voltage or low voltage grid connection. Recently there have been attempts [14,15,33] to charge the battery using inductive charging mechanism. In this mechanism, the power transfer from the source to the vehicle takes place through magnetic coupling. This is very much like a transformer with the primary winding placed with the energy source and the secondary winding inside the vehicle. The coupling of the fields from primary to secondary winding takes place through the air. Although the efficiency of such conversion is low due to poor coupling through the air, it has some distinct advantages. Those are, less maintenance due to no physical contact and safety due to no risk of shocks and sparks [14,15]. Other big advantage of this type of system is, vehicle battery can be charged at ease at various locations and its effective driving range can be increased. Fig. 13 shows the required infrastructure for contactless power transfer system. It has a line transformer to isolate the power line, a diode rectifier, a high frequency switching DC to AC converter which transfers AC power to the high frequency rectifier through air. A dc converter is connected after the rectifier to charge the battery.

If this infrastructure is placed at the traffic signals, parking lots and even on the roads while the vehicle is in motion, the battery can replenish its charge and effective driving range is increased.

3.7. Effective Thermal Management

In the countries having cold climate, the vehicles need to be heated in the winter. This heating reduces the driving range of the vehicle by about 50% [34]. If the energy loss in the electronics is effectively used for car heating, then this driving range can be restored to a great extent.

Thermal generators can also be used to aid the battery charging based on the temperature differentials in the various parts of the vehicle.

3.8. Impact of driving behavior

Driving style has a lot of impact on driving range of the vehicle. An interesting study performed in [35] concluded that about driving range can be improved by about 30% just by following the correct driving practices. Some of the good driving practices are as follows:

** Reducing the difference in acceleration and deceleration
** Avoiding high accelerations
** Reducing aggression in the driving

To reduce this impact of human behavior, seamless integration of technologies like Internet of Things (IoT) in the vehicle is necessary. With the sensors guiding the vehicle operation, the chances of errors are much less and effectively efficiency of the vehicle can be improved.

The Mohr-Coulomb (MC) and the linear Drucker-Prager (DP) failure criteria were chosen to represent the plastic deformation of the soil. Equations that correlate the friction angle and the cohesion between these two failure criteria already exist only for specific cases, e.g. triaxial compression or tension, plane stress/strain conditions, etc. However, in the rolling motion of a wheel, the problem becomes essentially three dimensional, in which case the various principal stresses are diverse and consequently there is not a unique way to match the one model to the other.

A novel relationship has been developed which can be used to approximately match the two constitutive models. The yield surface for DP is:

\[ P_e = k_e \times f^2 \times B_m^2 \]  

(8)

And the yield surface for MC is:

\[ P_e = k_e \times f^2 \times B_m^2 \]  

(9)

By setting equal the two normal vectors of the DP and MC yield surfaces at an arbitrary principal stress state, the following relations result:

\[ P_e = k_e \times f^2 \times B_m^2 \]  

(10)
\[ d_{DP} = 2c \cos \varphi \]  

The two last equations were used to convert the MC parameters to DP parameters in ABAQS and vice versa. The flow stress ratio in the DP model was set to unity which means that the yield stress in triaxial tension is equal to the yield stress in triaxial compression.

### 3.6. Mesh Adaptivity

During the modeling process of the indentation and the rolling procedure of the rigid wheel, high element distortion was observed on the soil, causing numerical errors and convergence instabilities. To avoid these issues the adaptive meshing (ALE) option offered in ABAQUS/Explicit was utilized in the simulation. One remeshing sweep every 10 increments was performed, where the calculation of the new mesh is based on the priority of improving the aspect ratio of the elements. The ALE was set only on the region of the model where the fine mesh was located. Given that ALE cannot be implemented in a parallel processing mode, the size of the mesh was minimized, since otherwise high computational cost may occur. A mesh sensitivity study has been performed and the final mesh size was chosen such that the reduction of the element size in successive refinements gave an error of lower than 5%.

### 4. Discussion and Impact Factor

From the information written in the previous sections, all the driving range improvement techniques can be categorized into three main categories. First one is improvement in the storage, second one is the improvement in the electronics and the third one is improvement in the drive train. To find out the impact of each of these techniques, an example of commercially available electric car is considered. This car uses a battery size of 30 kWhr and goes for 126 Miles per Gallon equivalent (MPGe). The efficiencies of motor, mechanical drive train and electronics are assumed to be 95%, 90% and 95%. The battery window of operation is assumed to be 90%. Table 1 shows the calculation for the driving range using Eqs. (5-7).

<table>
<thead>
<tr>
<th>Battery size (WHr)</th>
<th>30000</th>
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<tbody>
<tr>
<td>Miles Per Gallon equivalent (MPGe)</td>
<td>126</td>
</tr>
<tr>
<td>Energy required by the drive (WHR)</td>
<td>267.5</td>
</tr>
<tr>
<td>Efficiency of the motor</td>
<td>0.95</td>
</tr>
<tr>
<td>Efficiency of the mechanical drive train</td>
<td>0.9</td>
</tr>
<tr>
<td>Efficiency of the electronics</td>
<td>0.95</td>
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</tbody>
</table>

To quantify the effect of improvement, an impact factor is derived. Impact factor for this discussion is defined as driving range per unit of percentage improvement using various techniques.

Impact factor is calculated for the improvement of motor, electronics and initial battery energy. Fig. 14 shows these impact factors.

As seen from the figure, the improvement in the efficiency in the motor and drive train has less impact on the effective driving range. To have a sizable impact factor, significant improvement in the efficiency is required. With the efficiencies approaching 95%, this improvement is extremely difficult to achieve. On the other side, improvement in the storage has a big impact on the effective driving range. A small addition in the battery energy increases the driving range significantly.
Operating window of the battery | 0.9 |
<table>
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<tr>
<td>Effective Battery energy (WHr)</td>
<td>21930.75</td>
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<tr>
<td>Driving range (Miles)</td>
<td>82</td>
</tr>
</tbody>
</table>

Figure 14. Impact factor versus improvement in the various parts of the electric vehicle

5. Conclusions

Use of electric vehicles has been growing. Increasing the driving range of the electric vehicles is a topic of much interest in the commercial world. A detailed review of available methods to improve the driving range is presented in this paper. Driving range can be increased by using advanced storage materials, improving the converter technology, improving the motor, using renewables in the vehicles, on road contactless power transfer, effective vehicle thermal management and following efficient driving practices. Some of the promising technologies for the storage are lithium air batteries and hybrid storage solutions using ultra-capacitors and fuel cells. Converter and motor efficiency can be increased by using advance modulation techniques like pulse amplitude modulation and different winding patterns. An impact factor is derived to study the effect of each different technique of the driving range improvement. The improvement in the storage has highest impact on the effective driving range. Finally, although, impact factor of good driving practices is hard to calculate, it does affect the driving range. Hence, seamless sensor integration and Internet of Things (IoT) in to the vehicle would improve the driving range further.

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