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AN ANALYSIS OF SOLAR OPPORTUNITY RECHARGING FOR ELECTRIFIED TACTICAL VEHICLES

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ABSTRACT

The U.S. Army initiated a shift towards electrifying and hybridizing its tactical vehicle fleet in alignment with its Climate Strategy and global automotive trends. Survey findings indicate a general desire by soldiers for the ability to opportunity charge electrified tactical vehicles, especially in austere locations, with a focus on solar recharging. This study extracts, cleans, and analyzes geo-location data from a training exercise at the National Training Center at Fort Irwin, CA to identify the drive cycles for over 400 tactical vehicles. These drive cycles were then used to estimate the energy consumption per vehicle. The analysis then identifies how much energy can be provided by a 300 W solar blanket, deployed when a vehicle is stationary. The study found that the 300 W solar blanket under ideal conditions could offset approximately 10 percent of the energy required by the average vehicle. As such, solar energy has the potential to be useful for providing small amounts of energy that allow the vehicles to perform short-duration missions and provide power to accessories while idling.

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1. INTRODUCTION

In line with the U.S. Army's Climate Strategy and global trends toward sustainable transportation solutions, the U.S. Army started pivoting towards the electrification and hybridization of its military tactical vehicle fleet [1]. This move provides the warfighter with numerous new capabilities, as the vehicle fleet is able to leverage the most recent advances from the automotive community.

A recent study conducted a survey across the U.S. Army to identify soldier needs,

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wants, and desires for electrified tactical vehicles. The study found that soldiers perceived one of the large benefits of an electrified tactical vehicle is the potential for opportunity charging [2]. While diesel fuel remains important, especially for hybridized vehicles, a tactical vehicle operating in an austere location could potentially harvest energy from the environment rather than rely on fuel resupply. One technology commonly mentioned in the surveys is solar recharging.

This study seeks to better analyze how much energy is required by tactical vehicles during tactical missions and how much of that energy can be offset by solar recharging. The study leverages geo-location data for over 400 tactical vehicles as they perform a training exercise at the National Training Center (NTC) at Fort Irwin, CA, to determine each vehicle's energy expenditure. The analysis then identifies periods of time when the vehicles are stationary and could use solar energy to recharge the battery bank. The study then identifies the amount of energy expended by each vehicle that can be replenished by solar recharging.

2. BACKGROUND

This section details information about the U.S. Army's tactical vehicle fleet, the overall move to electrification, and the use of solar recharging.

2.1. Use of Tactical Vehicles

The U.S. Army employs a variety of tactical vehicles designed for versatility, mobility, and adaptability in a range of operational environments. Generally, tactical vehicles are wheeled and can be driven on roads, often with light armor to provide the occupants protection from small-arms fires and shrapnel. They also provide structure for mounting larger crew-served weapons.

Tactical vehicles differ from tracked combat vehicles which include armored personnel carriers, infantry fighting vehicles, and main battle tanks. Combat vehicles are typically much heavier, requiring substantially more power. As such, the electrification of these vehicles is a much larger challenge and was not included in the Army's Climate Strategy.

2.2. Move to Electrification

Secretary of the Army Christine E. Wormuth indicated that one of her major priorities is for the Army to promote sustainability initiatives in an effort to combat climate change [3]. As such, the Army released its climate strategy in 2022, which set milestones for electrifying vehicles in the Army fleet. In particular, the Army established a goal of fielding hybrid-drive tactical vehicles by 2035 and fully electric tactical vehicles by 2050 [1].

While sustainability may be a primary selling point for electric vehicles in the civilian sector, the military's use of JP-8 as a primary fuel source complicates the environmental argument. The majority of military power in the field feeds from generators burning JP-8, forcing the shift to electric vehicles into involving an additional step in converting the fuel.

Regardless, the tactical advantages of electric motors, such as increased torque, lower noise, and decreased thermal signatures, still make them appealing for military applications [4]. In particular, the decreased signature is expected to be a key advantage on the future battlefield.

Despite these benefits, technical challenges remain, particularly regarding battery weight and the logistics of recharging in austere environments.

This analysis considers a generalized case where the vehicle is either hybridized or fully electric. In either case, the vehicle has a considerably large battery bank, which can be recharged from an external power source, in this case solar energy.

2.3. Use of Solar Recharging

A recent survey conducted among soldiers indicated that one of the benefits of electric vehicles is the opportunity to cut reliance on fuel resupply [2]. In particular, while the vehicle can be recharged from a generator powered by JP-8, there is the potential for the vehicle to also be recharged from other sources. For example, the vehicle could be recharged from a local grid.

In austere areas, these vehicles may not have reliable access to fuel resupply. However, the vehicles still require sufficient energy to perform assigned missions. One possible option is solar recharging. Indeed, dismounted soldiers already use solar blankets for opportunity recharging of their batteries while in remote locations.

A common size for a solar blanket is 300 W, which is approximately 24 square feet and weighs approximately 10 kg. These blankets typically use monocrystalline silicon cells which are inexpensive and have an efficiency of 12 percent. These blankets are commonly used by campers and other groups operating in remote areas. While dismounted soldiers typically use smaller 120 W blankets, the energy demands for a vehicle is substantially larger, so this study used a 300 W blanket.

Figure 1 shows the basic schematic of a solar cell. The amount of power output is based on the incidence angle between the solar ray and the surface of the solar blanket. In particular, the blanket only produces 300 W when the sun is directly overhead on a clear day. However, as the incidence angle changes, the power output decreases.

3. METHODOLOGY

This section details the methodology used for the data analysis including the extraction of geo-location data from the NTC Dataset, developing drive-cycles, calculating energy consumption, and calculating the solar energy produced.

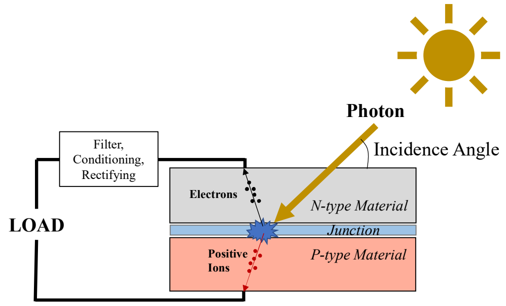

Figure 1: Schematic of how photovoltaic cells generate electricity.

3.1. National Training Center Dataset

The current Army mission model involves the deployment of Brigade Combat Teams (BCTs), with 60 BCTs divided between Active Duty and Reserve Components. Each BCT, comprising approximately 4,000 personnel, undergoes realistic training to be effective in combat. The National Training Center (NTC) at Fort Irwin, California, serves this purpose and spans 11,000 square miles of mock-up villages and diverse terrain. During a month-long rotation at NTC, a BCT, known as the Blue Force (BLUFOR), engages the Opposing Force (OPFOR) led by the 11th Cavalry Regiment. The training involves force-on-force exercises and a live-fire event, with observer/controllers evaluating performance.

Soldiers and equipment use Multi Integrated Laser Engagement System (MILES) gear, incorporating GPS locators and laser transmitters for combat simulation without live rounds. Of importance to this study, the MILES gear logs the GPS location of vehicles as they maneuver throughout the training exercise. Data from MILES gear is stored in the National Training Center-Instrumentation System (NTC-IS), a database with over 300 tables, enabling longitudinal analysis. Maintained by the Training and Doctrine Command Intelligence Cell, the NTC-IS database holds about 2 GB of data per rotation, comprising 12 million rows of data. This data, compatible with SQL developer, R, MATLAB, or Excel, includes various views for research.

3.2. Extracting a Drive-Cycle

This study follows the data analysis process outlined in Figure 2 to extract the necessary data from the NTC dataset to build out a vehicle drive-cycle [5]. The drive-cycle is characterized by knowing the distance travelled and elevation changes over the length of the training exercise.

After loading the dataset (D), it is filtered to isolate data related to a specific vehicle type. This filtering generates a subset of D, annotated as D1. Each unique vehicle in D1 has a vehicle identification number. The list of unique vehicle identification numbers is extracted from D1 and stored as V1. The algorithm then individually analyzes each unique vehicle. D2 is a subset of D1 that pertains to an individual vehicle, identified by its identification number. Corrupted position and time data within D2 are removed through data filtering. The dataset is then sorted based on time to organize the data chronologically.

Within D2, the algorithm computes variations in longitude and latitude between consecutive time steps and transforms these changes into distances. The vehicle's elevation data is acquired at each time step from a digital topographical terrain map based on its longitude and latitude. These distances and elevations are compiled to construct profiles illustrating distance-versus-time and elevation-versus-time.

Further, when the vehicle is turned off, the MILES gear powers down, resulting in no data being collected during that time period. As such, the algorithm can identify when the vehicle is turned off.

The dataset does not have uniform time steps, with variations in time-steps ranging from milliseconds to minutes. To enable subsequent analysis, interpolation is executed on the distance and elevation profiles at consistent time intervals. Notably, At the shorter end of the spectrum, discrepancies in the GPS data can lead to artificially high velocities. To uphold data integrity, a validation process is implemented to identify non-corrupted data points.

Following the interpolation, the distance and elevation profiles for each vehicle can be converted to velocity and grade profiles. The velocity profiles are calculated by subtracting the distances at consecutive time steps. The grade profiles are calculated by dividing the change in elevation by the change in distance from consecutive time steps.

This analysis also requires identifying when the vehicle is turned off, as opposed to idling. When the vehicle is turned off, the MILES gear stops logging the GPS positions. As such, this analysis is able to distinguish when the vehicle is turned off by identifying large gaps in time where the data is not logged.

```
D = Imported dataset
D1 = D filtered to tanks
V1 = List of unique identifiers in D1
For j = 1 to length(V1)
  D2 = D1 filtered to individual vehicle ID
  Filter D2 to remove corrupted position and
    time data
  Sort D2 based on time
  For k = 1 to length(D2)
    Determine change in long. and lat. from
      one time step to next. Convert to
      change in distance.
    Lookup elevation data from terrain map
      for long. And lat.
  Aggregate distances to make a distance vs
    time profile
  Aggregate elevation to make an elevation vs
    time profile
  Interpolate distance and elevation
    profiles at fixed time steps
  Check to ensure non-corrupted data
  Divide the change in distances by the
    uniform time step to generate a velocity
    profile
  Divide the change in elevation by the
    Change in distance to generate a grade
    profile
Aggregate the results for all tanks
```

Figure 2: Algorithm for data extraction to develop vehicle drive profile.

Table 1. Constants used in data analysis.

Parameter	Symbol	Value
Drag Coefficient	C_d	0.5
Rolling Resistance Coeff	f_0, f_s	0.014, 0.01
Density of Air	ρ	1.15 kg/m^3
Mass of vehicle	M	11,000 kg
Frontal Area of Vehicle	A	10 m^2

3.3. Calculating Energy Consumption

The power consumption for each vehicle is calculated at each time step as being the sum of the power necessary for the vehicle to increase/decrease in velocity, overcome air drag, overcome rolling resistance, traverse an incline, and power accessories [6].

At each time step, the following variables are determined from the NTC dataset:

- v : instantaneous velocity (m/s)
- θ: incline (rad)

Additionally, a number of constants had to be defined for the vehicle. These constants are summarized in Table 1.

Figure 3 shows the algorithm for determining the total energy consumed by each vehicle after developing a velocity and incline profile. At each time step, it is first determined if the vehicle is on or off. If the vehicle is on, the power for acceleration, overcoming incline, overcoming drag, and overcoming rolling resistance is calculated at each time step.

If the power is negative (i.e., the vehicle is decelerating), the analysis assumes that the vehicle is able to capture some of that energy through regenerative braking at a 65 percent efficiency [7].

Additionally, the power required for accessories, such as the radio and electronics, is included in the total power required at a given time step. This value is set at 1000W, which is approximately the power required for two radios and a remote-control weapon platform [8].

The power required at each time step is then multiplied by the time step to determine the energy required at that time step. The total energy per vehicle is then calculated by summing across all time steps.

```
v = velocity profile with interval Δt
θ = incline profile with interval Δt
For j = 1 to length(v)
 If Vehicle is On
   Calculate power for acceleration
     $P_{accel} = mv_j\,(v_j - v_{j-1})/\Delta t$
   Calculate power for incline
     $P_{inc} = mg\,\sin\theta\;\, v_j$
   Calculate power for drag
     $P_{drag} = 0.5\, C_d A \rho\, v_j^3$
   Calculate power for rolling resistance
     $P_{roll} = mg\left(f_0 + 3.24 f_s (v_j/223)^{2.5}\right) v_j$
   Calculate power for accessories
     $P_{acc} = 1000\, W$
   If ($P_{accel} + P_{inc} + P_{drag} + P_{roll} > 0$)
     $P_j = P_{accel} + P_{inc} + P_{drag} + P_{roll} + P_{acc}$
   Else
     $P_j = 0.65\,(P_{accel} + P_{inc} + P_{drag} + P_{roll}) + P_{acc}$
 Else
   $P_j = 0$
 Multiply $P_j$ by $\Delta t$ to get energy consumed
Sum over all time steps for total energy consumed
```

Figure 3: Algorithm for calculating the amount of energy required by vehicle.

3.4. Calculating Solar Energy Generation

This analysis assumes that each vehicle is outfitted with a 300 W solar blanket. Such a blanket produces 300 W of electricity when the sun is directly overhead, such that the beams are normal to the panel. The power output degrades based on the angle of the sun relative to the blanket. The blanket is assumed to be on a flat horizontal surface, such that the incidence angle is only a function of the time of day.

The time of day is characterized by a variable (*TOD*) that went from 0 to 1, where 0 equates to 12:01AM, 0.5 equates to noon, and 1 equates to 11:59PM. When *TOD* has values between 0.28 and 0.71, the sun is visible, and the solar panel is producing energy. During this period, the power output is approximated by Equation 1.

$$P_{solar} = (300W)\sin(TOD \times 7.33 - 2.1) \quad (1)$$

This approximation assumes that the skies are clear and that the solar panel is clean with an unobstructed view of the sky.

4. ANALYSIS

The algorithms discussed in the previous section are implemented to determine the energy consumption and the amount of solar energy harvested for each vehicle over the training exercise.

4.1. Vehicle behaviors

The data from NTC provides insight into how much the tactical vehicles are used on a daily basis. Figure 4 displays the average percent of the day that each vehicle spent off, idling, and moving. On average, vehicles are only moving 4.8 percent of the time; this equates to 70 minutes. Meanwhile, the vehicles are idling for an average of 25.5 percent of the day, approximately 6 hours. The rest of the time, the vehicles are turned off. These results are consistent with other studies that have identified a substantial amount of idling time [9].

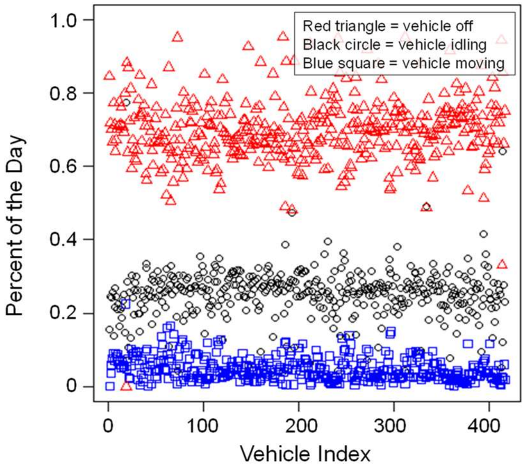

Figure 4: Percent of the day each vehicle spent turned off (red triangle), idling (black circle), and moving (blue square).

4.2. Vehicle energy consumption

Figure 5 displays the energy consumption over the training exercise using the analysis discussed in Section 3.3. The tactical vehicles use 2060 MJ on average, with a standard deviation of 1395 MJ. The highest energy consumption is 7643 MJ, and the least energy consumed is 12 MJ. This analysis does not consider vehicles that are completely stationary over the training exercise or those with corrupted GPS readings.

Figure 6 plots the average daily miles driven by each vehicle against the average daily energy consumption over the exercise. As expected, increased vehicle mileage results in an increase in the amount of energy consumed, since the bulk of the energy is expended for locomotion. The 1000W of power required when the vehicle is idling is considerably less than the power required when the vehicle is moving.

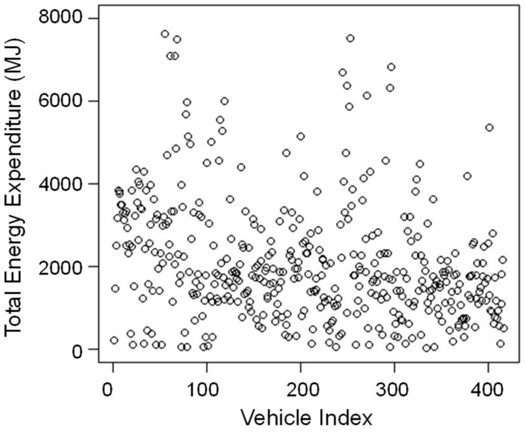

Figure 5: Total energy expenditure over the training exercise for each tactical vehicle.

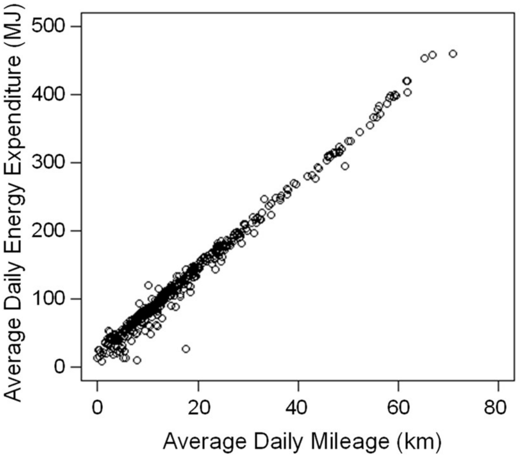

Figure 6: Average daily mileage plotted against the average daily energy expenditure for tactical vehicles.

4.3. Solar production

Figure 7 plots the total solar energy harvested by each vehicle over the training exercise. The analysis found that with clear skies, the average vehicle would be able to harvest 106 MJ of solar energy, with a standard deviation of 30 MJ. The maximum amount of energy harvested is 161 MJ for a vehicle that is primarily stationary for the duration of the training exercise.

The amount of solar energy harvested is a function of the amount of time that the vehicle is stationary. Many of these vehicles remain stationary for extended periods of time. Figure 8 plots the average daily solar energy output against the percent of the day that is spent stationary. Notably, most of the vehicles are stationary for more than 95 percent of the day. Additionally, they produce an average of 7 MJ from the 300 W solar blanket over the course of the day.

4.4. Offset of energy by Solar

Figure 9 plots the percentile of vehicles against the percent of energy that can be offset by solar energy with a 300 W solar blanket. This assumes that the energy transfer from the solar blanket to the vehicle's battery banks does not have any major losses (i.e., 100 percent efficient transfer of energy).

The analysis found that less than 2 percent of vehicles are able to offset more than 50 percent of their energy from the 300 W solar blanket. Meanwhile, more than half of the vehicles are able to offset 10.1 percent of their energy.

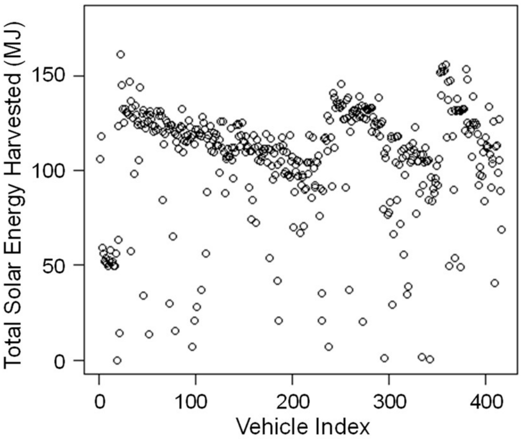

Figure 7: Total solar energy harvested over the training exercise assuming that a 300W solar blanket was deployed whenever the vehicle was stationary.

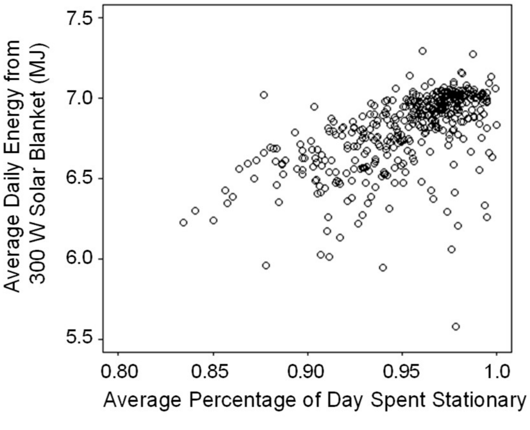

Figure 8: Average daily solar energy harvested from a 300 W solar blanket plotted against the average percentage of the day spent stationary.

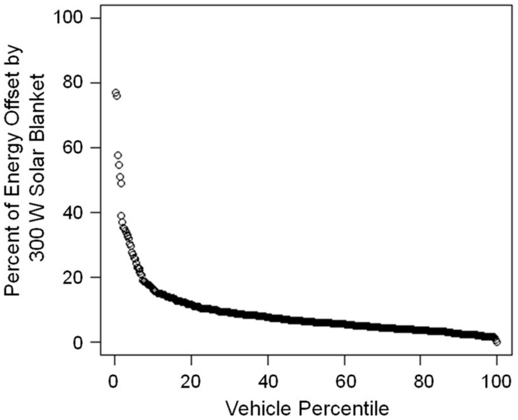

Figure 9: Percent of vehicle energy that was offset by 300 W solar power plotted against the percentile of vehicles.

4.5. Fuel Consumption

This study focused primarily on the energy required by the vehicle over the training exercise. However, from a logistics standpoint, it is important to consider the source of this energy. In particular, for conventional vehicles this energy is provided by the combustion of JP-8 in the engine.

A method for performing fuel consumption estimates based off energy consumption is provided in [10]. The process assumes a standard diesel engine curve with a peak efficiency of 8 percent at idle and increasing to 33 percent at peak load. The resulting analysis found that the average vehicle consumed 10.2 kg of JP-8 per day while moving and 24.5 kg of JP-8 per day for idling. The 34.7 kg of fuel required equates to approximately 11.5 gallons of fuel consumed per vehicle daily.

If the vehicle has been hybridized or electrified, the vehicle can then leverage the battery pack for the idling conditions, which would reduce the fuel consumption. Moreover, the vehicle would be able to take advantage of the opportunity recharging discussed in this paper.

If the battery packs are providing power to the vehicle when idling and the depleted battery packs are recharged by the engine when the vehicle is moving, the average daily fuel consumption is reduced to 20.1 kg. This fuel savings is substantial.

The reduction in fuel consumption from the incorporation of a 300W solar blanket would further reduce the fuel consumption to 19.0 kg. Although this reduction is small when compared to the fuel saving from using a battery pack when idling, this fuel savings is not negligible.

4.6. Size and Cost Solar Blanket

This analysis used a 300 W silicon solar blanket which has a footprint of 2.4 square meters. Discussions with stakeholders indicated that larger solar blankets would not be desirable since they would be difficult to deploy and to fold up for storage. However, the amount of energy that is produced by the solar blanket would be directly proportional to the size of the blanket.

Figure 10 plots the average percent of energy offset by solar against the power output from the solar blanket. The plot also gives the associated size of the solar blanket assuming an efficiency of 12 percent, a standard value for silicon foldable blankets. If the blanket is 24 square meters, it would offset the full energy requirement for 50 percent of the vehicles.

This analysis assumed a standard silicon cell with a 12 percent efficiency. Other materials could potentially provide a higher efficiency. For example, copper indium gallium diselinide cells have been measured to achieve efficiencies of 24.3 percent. While significantly more expensive than the more traditional silicon, the size of the solar blanket would be half that of the standard silicon [11].

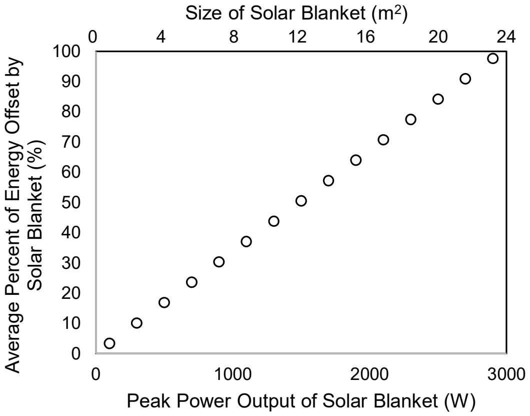

Figure 10: Average percent of vehicle energy that was offset by solar blanket plotted against the peak power output and size of the solar blanket

5. OTHER IMPLICATIONS

While the previous section focused on the energy requirements of tactical vehicles and the percent of energy potentially offset by solar recharging, there are a number of other considerations that must be considered. This section discusses those implications.

5.1. Combat Implications

Soldiers may be hesitant to adopt solar recharging for electrified tactical vehicles due to concerns about maintaining cover and concealment during recharging. In military operations, staying hidden is critical for safety, but solar blankets used for recharging require direct sunlight, making it challenging for soldiers under concealment in shaded or covered areas. These blankets are often reflective and shiny, potentially attracting attention and revealing the soldiers' position to adversaries, especially with the increased use of unmanned aerial vehicles on modern battlefields.

Moreover, the process of setting up and repacking solar blankets is time-consuming, hindering the soldiers' ability to quickly move and adapt to changing situations. Traditional fuel-based vehicles can be refueled without revealing their location, providing a tactical advantage in terms of stealth and mobility. The perceived trade-off between the need for sunlight and the risk of exposure may make soldiers wary of relying on solar recharging solutions in scenarios where maintaining covert positions is crucial for mission success. Finding ways to address these challenges, perhaps through improved camouflage or portable solar solutions, are essential for gaining soldier acceptance of solar recharging in tactical environments.

Meanwhile, opportunity charging provides additional versatility for tactical vehicles. In particular, analysis finds that the bulk of the driving is for short distances, with the average trip being approximately 10 km followed by long stops. Solar opportunity charging allows an electrified tactical vehicle to maintain a state of charge while conducting operations in environments where refueling may not be available.

5.2. Sustainability Implications

While the driving factor for electrifying tactical vehicles is the Army Climate Strategy, it is important to note that this process may not have a large impact on the Army's overall logistics footprint.

Indeed, solar opportunity charging is intended to be a method for soldiers to acquire extra energy for their vehicle while they are stationary to top-off their battery packs. Hybrid tactical vehicles still use diesel fuel to provide a portion of the energy for locomotion. A fully electric vehicle would likely be recharged by a generator set at a rear location, resulting in fuel combustion being simply off-boarded from the vehicle.

Regardless, an electrified tactical vehicle provides the benefit of reduced fuel losses to idling. Such benefits would have a large impact on an infantry brigade combat team, where the primary fuel consumers are tactical vehicles. However, the benefits would be small for an armor brigade combat team, where most of the fuel is consumed by the heavier combat vehicles. By comparing refueling requirements for the different vehicles in the armor brigade combat team, the wheeled tactical vehicles would account for less than 5 percent of the total fuel usage by vehicles.

6. CONCLUSIONS

Efforts by the U.S. Army to electrify its tactical vehicle fleet are often seen as a sustainability benefit, especially since this effort is predicated on the Army Climate Strategy. However, this effort is more than just about sustainability. It allows for the Army to leverage the advances in an automotive community that is also moving towards electrification. In doing so, the Army can provide new benefits to the warfighter. One large benefit for electrified tactical vehicles is opportunity charging, where the vehicle battery packs can be topped off by solar power. In doing so, the vehicles are less reliant on fuel resupply.

This study analyzed over 400 vehicles conducting a training exercise at NTC. It approximated the energy consumption of the vehicle as the vehicles maneuver on the battlefield. The study found that the vehicles are stationary the bulk of the time. While there are large periods of time when the vehicles are off, they also idle for a considerable amount of time. This provides the time necessary for opportunity charging. This study found that approximately 10 percent of the energy used by the tactical vehicles could be replaced by solar energy. Further, the contribution of solar would increase as solar technology becomes more advanced, tactical vehicles become lighter, and electronics become more efficient.

The contributions of solar are inherently limited. For most standard mission sets, the vehicles would still be reliant on fuel. However, as soldiers operate in austere environments without reliable access to fuel, solar recharging would provide enough energy for limited movements and to power the electronics when the vehicle is stationary.

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