Optimising Race Strategy of a PV Vehicle Considering the Effects of Dust Accumulation on Solar Panels

DESIGN CHALLENGE

Recommendations

DLab2 World Solar Challenge

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1 Introduction

The majority of the 2017 World Solar Challenge route is through an arid desert region, and during the dry and potentially windy period of October, air dust content is expected to be high. Vehicle owners who travel long distances regularly will be familiar with dust build-up on a vehicle, in particular on the windscreen inhibiting vision. This dust build-up however has far direr consequences on a solar vehicle which is reliant on attached photovoltaic panels capturing energy from the sun and converting it to electrical energy. The ANU Sol Invictus team can expect dust-build up throughout their journey and managing cleaning of these particulates from the solar panels is a key component to race strategy and could impact their finishing position.

1.1 Photovoltaics and Performance

Photovoltaics fitted to solar vehicles are similar to those commonly utilised in energy production on household rooves and in solar plants, and share a similar limit to efficiency (Mani & Pillai 2010). Whilst technological advancements continue to improve efficiency, energy production is ultimately restricted by the amount of incident sunlight. In a competitions such as the WSC, which restricts solar harvesting by catchment area (*2017 Regulations*, WSC), maximum performance requires maximum panel area. Any particulates which develop on the surface of a solar cell ultimately reduce the panel area available for energy production and thus lower performance. Understanding the magnitude of this impact is critical to race strategy as even a minute performance drop per kilometre will have a significant effect over a 3000km journey.

1.2 Dust Accumulation and Performance

Whilst the accumulation of dust on rooftop household solar panels has been proven negligible (Ghosh & Ghosh 2014), the build-up anticipated on a competition solar car travelling at highway speed is expected to be significant. Particularly considering the desert location, and the high volume of traffic expected in the region during the challenge. Recent editions of the WSC have also demonstrated very close margins between competitors and small performance improvements have the potential to determine a team's finishing position (*Challenger Class Outright Results*, WSC). A simple Fermi estimation demonstrates the magnitude of performance that is at stake:

Assume power is proportional to speed: 1% power reduction = 1% speed reduction

speed loss = 0.01 x 100 km h^{-1} = 1 km h^{-1} → 8 hours driving per day = 8 km loss per day

This validates serious concern over dust build-up degrading panel performance, and the solution is certainly non-trivial, however through a systems analysis it is an approachable problem. Thus, the research question, *how often should the ANU WSC Team stop their PV vehicle specifically to clean its solar panels and what gain is entailed,* became the focus of the analysis. Through extensive research, algorithm development, systems and analytical methods a simulation and database were developed, referred to as *DusTime*.

2 Outline of Recommendations

In order to address the research question specifically and further aid the client, the DusTime system is provided to the Sol Invictus team accompanied by a series of recommendations pertaining to its use:

MAJOR RECOMMENDATIONS

R1 **Combine live and static usage of *DusTime* system**

R2 **Respond immediately and in accordance with *DusTime* outputs**

SUPLEMANTARY RECOMMENDATIONS

R3.1 **Determine and reduce total time loss due to stopping**

R3.2 **Follow procedure for panel cleaning**

R3.3 **Utilise cleaning opportunities when integrated with other race strategy**

3 Design Basis of *DusTime*

To address the question of if and when Sol Invictus should schedule a stop for cleaning the solar panels, a simulation was selected as it meant an unlimited number of complex factors could be incorporated. Furthermore, in the case where the impact or value of a factor was too uncertain to be fixed, a series of simulations could be developed to form a database. Since a plain simulation is not particularly useful to the WSC team, an interpretable output was critical. Consequently, the simulation was built around developing a *payback period analysis*. However, since the race is determined based on performance rather than money (the way payback periods are typically considered in business and engineering), the currency used along the y-axis of the pay-back chart was changed to distance. In order to develop an accurate estimation of the race distance payback period for a cleaning stop, a detailed algorithm was developed.

3.1 Algorithm

The MATLAB implementation (see Appendix) is based on an algorithm in time steps of one minute over a given period. In each simulation step, the amount of dust on the panels is calculated according to the dust rate input. This is then used to calculate the power output decrease of the panel which in turn is used to calculate the speed that the car can travel for that power output. The speed is then used to calculate the distance covered in that minute, then added to a distance counter for graphing purposes (Appendix Figures A1-A6).

3.1.1 Linear regression

In order to calculate the power loss from dust and speed limit due to power decrease, data from various research papers were used (see Section 3.2). From this a series of *x-y* pairs were generated and modelled with a line of best fit. The dust build-up rate was specified at the start of the program, and assumed to be linear. Due to the assumption that it was a linear rate, *simple linear regression* was used to calculate the amount of dust at any time given a dust amount at 0 and 1 hours. This relies on the use of regression and the accuracy of the data collected by a third party (El-Shobokshy & Hussein 1993, Saiden et. al. 2016). In several cases, the trends between variables were more complicated and required more complex curve fitting techniques.

3.1.2 Cubic interpolation

The data points for the 'power vs speed' relationship were interpolated using MATLAB to find the most accurate value for a desired *x* value that was not specified in the initial data set. The interpolation function used in MATLAB was 'spline', which performs cubic interpolation. Utilising cubic interpolation was critical in ensuring that the curve present in the original data was not overly simplified into a series of straight lines, compromising accuracy.

3.2 Assumptions and Error Types

A simulation output is entire dependent upon the values prescribed for the inputs. To make the analysis as accurate as possible, values were developed from academic journals where possible. In some cases, calculations had to be based on theoretical relationships which are not always observed in practice and this is a limitation of the analysis. The two most uncertain factors *stop time* and *dust rate build-up* are unique to the solar vehicle and thus became independent variables for the simulation.

The **maximum speed** of 110 km h^{-1}, was selected in the static analysis based on other teams who have competed in past editions predicting similar values (Boulgakov 2012). Furthermore, the 'Power vs Speed' data used later in the analysis was also available from 0-110 km h^{-1}. During the challenge there is an opportunity for the team to feed live data about speed into the simulation which will improve accuracy.

The **simulation length** was held constant at 4 hours as this matches the maximum time a driver can complete in one stint (*2017 Regulations*, WSC). Shorter durations which are likely to occur during the race can be determined by reading up to that point on the payback period chart. This method did assume that during any other stops the team cleans the panels, restoring them to 100% efficiency.

The **stop time** was defined as the total time loss compared to another vehicle remaining at constant, maximum speed. This includes not only the time to physically clean the panels but the time loss during deceleration and more importantly acceleration. As Sol Invictus has not released details about motor performance or aerodynamics, quantifying this was difficult. Thus for the static analysis each payback-period chart shows outcomes based on a series of stop times between 2 and 10 minutes. Again once at a prototype stage the WSC team has the opportunity to refine this.

The **stopping point** was always set at the centre of an interval, dividing it equally into two halves. This forms the optimal stopping point as performance is spread evenly either side. If the team stop prior to the halfway point, the analysis is simply reset to 0 km. If they want a prediction for delaying a stop beyond the halfway point a simple adjustment to the simulation is provided.

The **particle size** of dust in the Northern Territory and South Australia was averaged based on *descriptive statistics* from a series of academic research papers, giving a value of 80um, which is typically associated with ground limestone, cement dust and sand tailings (Mani 2010, El-Shobokshy & Hussein 1993)

The **dust build-up rate** was assumed to be linear, that is that weather conditions over the given interval are constant and the amount of dust accumulated does not affect the future rate of build-up. This is potentially an example of *sampling error* whereby the complete range of conditions were not considered owing to undue complexity. Furthermore, as dust accumulation rates have only been published for stationary panels, a range of dust build-up rates based on (Mejia et. al. 2014) are provided for the static analysis (5 – 30 g $h^{-1}m^{-2}$) and the team can simply match their observed rate with those provided.

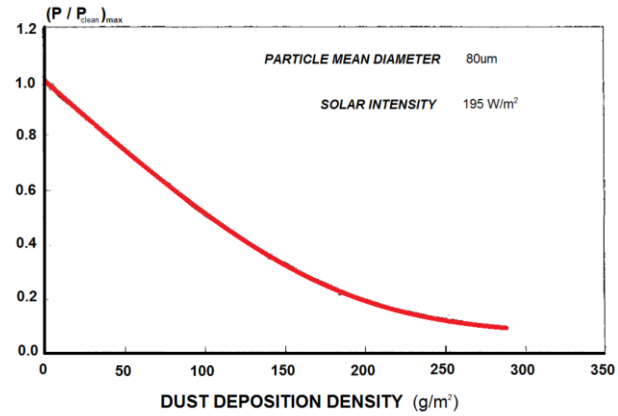


Figure 3.1 Dust effect on power (%) for mean particle diameter of 80um and solar intensity of 195 W m^{-2}. Graph redrawn from data provided in El-Shobokshy & Hussein (1993).

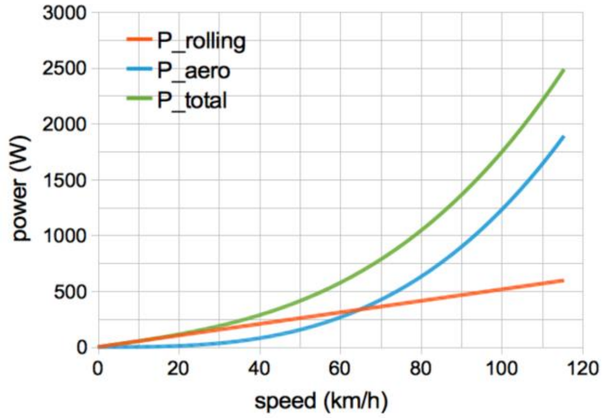


Figure 3.2 Power consumption vs speed for Sunswift IV (2009) on a flat road with no wind, which is a reasonable comparison to ANU's 2017 attempt. From Boulgakov (2012).

The **effect of dust on power** was derived from Figure 3.1 (El-Shobokshy & Hussein 1993) corresponding to particle sizes of 80um, and corresponding results have been published in other papers for other particle sizes (Sayyah et. al. 2014, Sulaiman et. al. 2014).

The relationship between **power and speed** requires details on both motor efficiency and aerodynamics which are not yet available for the ANU team. Thus values from a 2009 Competition car (Boulgakov 2012) were agreed to be within range of ANU's first attempt at a PV vehicle (see Figure 3.2).

4 Detailed Recommendations

R1 Combine live and static usage of *DusTime* system

The DusTime system designed can function in two forms, statically and based on live data. Whilst operating using only the static data, the team will need to compare the currently observed conditions to that of the quick reference lookup table (see Table 4.1) or the more detailed pay-back period charts (Appendix Figure A1-A6), which will inform the best choice on stopping to clean the solar cells or continuing without.

Table 4.1 Quick-Reference Look-up Table using Static Data

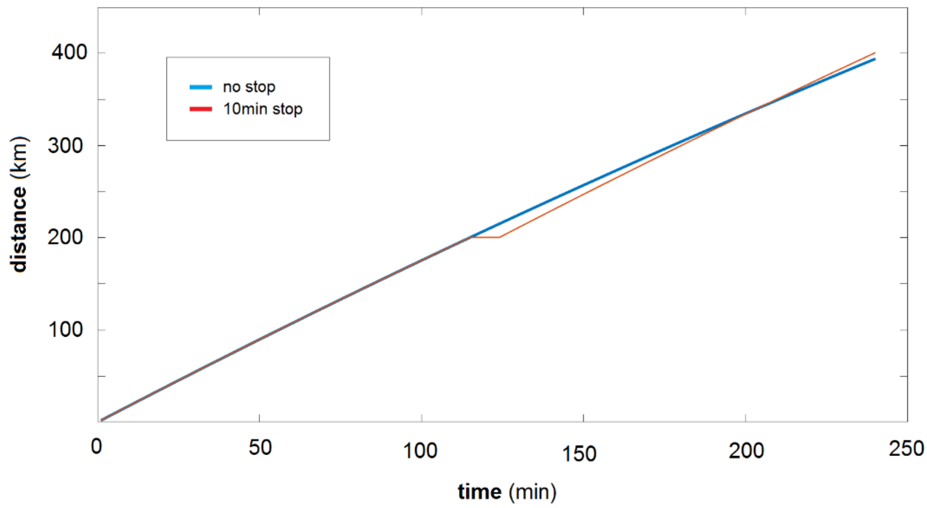
Dust Accumulation Rate (g h^{-1} m^{-2})	**Maximum stop time*** (min) (±1min)	**Maximum gain**** (km)
5	4	0.1
10	6	6.1
15	10	12.0
20	12	17.6
25	16	22.7
30	18	27.3

*Maximum length stop time (including slow-down and speed-up as defined in Section 3.2) that can be made whilst still being quicker than not stopping at all.

**Maximum kilometre gain over a 4 hour period

However, during the race, it is far more likely that the team will be receiving live data from the solar vehicle via telemetry. While operating using live data, the DusTime system can incorporate live speed data, dust build-up and performance rates which tailor the results to the current conditions. This allows the Sol Invictus team to implement DusTime as a *control system,* inputting the current conditions (the sensory component) and using the output to determine the best course of action (see Recommendation 2). Whilst this live simulation is more accurate, the static charts and tables provided here (for example Figure 4.1) are expected to be good indicators of general trends and are anticipated as useful tools when making strategy decisions on the fly.

Figure 4.1 Example Payback-period chart comparing a 10 minute stop loss to not stopping (20 g h^{-1} m^{-2}). See the Appendix for extensive payback-period charts for all conditions.



R2 **Respond immediately and in accordance with *DusTime* outputs**

The risk in stopping to clean the solar panels is significant in terms of race performance; should the time required to stop, clean and accelerate outweigh the efficiency gained, it not only disadvantages Sol Invictus but also unduly complicates strategy. There are also several other risks involved with stopping, all of them have the outcome of losing the team overall time in the race. These include stopping where the car would not benefit from extra efficiency, stopping causing a vehicle malfunction and stopping where it is likely the team will be overtaken while doing so (where the gained efficiency may be wasted while trying to re-overtake). To control this risk, a hierarchy of control was used. When developing strategy calls it is recommended the team combines the DusTime results with risk management strategies (see Table 4.2) and the well-established hierarchy of controls.

Table 4.2 Risk Management Strategies for Consideration in Consultation with DusTime Outputs

Risk Area	**Control measure** (as per hierarchy of control)	**Reasoning**
Time lost due to stop	Elimination (no stop performed)	If the time gained is insignificant, complicating the situation with a cleaning stop would have a negative impact. This situation is similar to Occams razor, which says that the simplest course of action is usually the best.
Vehicle malfunction	Engineering Controls	The vehicle should be able to stop consistently and safely as per the construction requirements. For this reason, the risk was assumed insignificant.
Low efficiency payback*	Elimination (no stop performed)	As no time will be gained (the car is already performing at peak performance and no stop is required.
Overtake likely (imminent or recently executed)	Administrative controls	This risk is highly situational, requiring that the team further asses if the gains made will be greater than the disadvantage of being overtaken. The team will need to develop specific strategies in accordance with this risk which will be outside the scope of the DusTime system.

***Car will not benefit from increased efficiency** *(battery is already charged, low power demand due to terrain etc.)*

SUPPLEMANTARY RECOMMENDATIONS:

R3.1 **Determine and reduce total time loss due to stopping**

The total time loss due to stopping will depend on the dust build up rate in the solar panels. Therefore, it is recommended to determine and accumulate data during the race as to know which simulation to use. This will make future predictions more accurate. From the simulations, it can be seen that the higher the dust build-up rate, it is more efficient to stop and clean the panels at least once between driver changes. On the other hand, if the dust build-up rate is lower it is recommended to assess previous stopping times to see if a stop is necessary.

R3.2 **Follow procedure for panel cleaning**

It is important to follow procedures because if all the dust is not removed when cleaned and the panels do not return to 100% efficiency, race strategy and the entire analysis is rendered invalid. Furthermore, the procedure which leads up to the actual event of cleaning is critical to avoiding mistakes during the stoppage time. To demonstrate the high stress areas *planning approaches* were applied to develop a network diagram (Figure 4.2) and a Gantt chart (see Appendix Figure A7). It is important to note that once a stop is triggered by informing the driver, the team has very little time to prepare. Thus *parallel processes* such as preparing clothes and personnel for the stop must be performed in advance of triggering the stop. This evident in the limited amount of slack inherent in these tasks and must be a consideration when acting on the DusTime system.

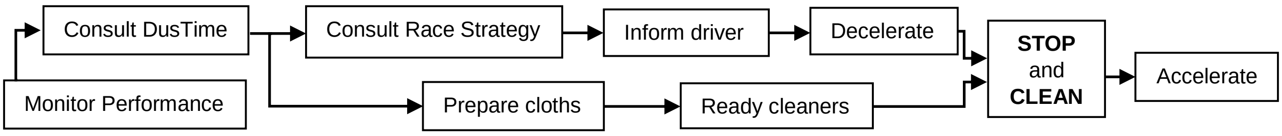


Figure 4.2 Network diagram demonstrating the flow of events leading up to and following a cleaning stop

R3.3 **Utilise cleaning opportunities when integrated with other race strategy**

Utilising solar panel cleaning opportunities is only one part of optimising the race strategy, as there are many more factors such as control stops, driver changes, and tyre changes. If a stop is needing only for wiping the solar panels, it is recommended to stop on a hill to reduce the amount of energy needed to accelerate back to cruising speed. Altitude data can be sourced from other groups which have analysed optimal stopping points along the route. It is recommended that if a stop is needed for any other reason, that the panels be wiped as they will take the shortest amount of time. To make conflicting decisions, a process control/risk management approach can be used to determine the best outcome.

5 Limitations and Alternatives

An alternate solution to preventing dust building up solar cells are hydrophobic and hydrophilic coatings. Hydrophobic coatings repel water, particles, dirt and dust due to the adhesive forces decreasing between the two surfaces (Smitha et. al. 2016). This theoretically should maintain panel performance; however due to variations particle types and contact angles, hydrophobic coatings slow the dust accumulation rate rather than prevent it (Faithi et. al. 2016). Hydrophilic coatings which operate by attracting water to form an evenly spread water barrier that prevents the adhesion of dirt and dust to the surface are also flawed (Hu et. al. 2015). It is not only impractical to maintain a wet surface when driving in a dry area and secondly, the World Solar Challenge regulations do not allow cooling of the panels which would occur if maintaining a wet surface (*2017 Regulations*, WSC). Although both hydrophobic and hydrophilic coatings slow the build-up of dust particles and dirt they remain in preliminary research phases, and do not completely eliminate the adhesion of solid particles. This reinforces the importance of the aforementioned analysis and highlights its continued relevance to the ANU Sol Invictus team even in future additions of the challenge.

6 Conclusion

Through a MATLAB simulation, the viability of stopping to clean dust from a solar vehicle in the WSC has been considered. A payback-period analysis has been modelled for a variety of conditions to aid Sol Invictus in optimising their race strategy. Additionally, through the application of systems analysis it is recommended that DusTime is used in both live and static forms, and with consultation of the provided risk management strategy. Sol Invictus are reminded that understanding procedure and the analysis' limitations are critical to its success.

7 References

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Sulaiman, S, A, Singh, A, K, Mokhtar, M, M, M & Bou-Rabee, M, A 2014, *Influence of Dirt Accumulation on Performance of PV Panels,* Energy Procedia, Vol. 50, pp.50-56

2017 Regulations, 2016, World Solar Challenge (WSC), Technical Report, Version 1.0, Issue 5 June 2016

8 Appendix

Figure A1 Payback-Period Chart for Dust Accumulation Rate = 5 $gh^{-1}m^{-2}$

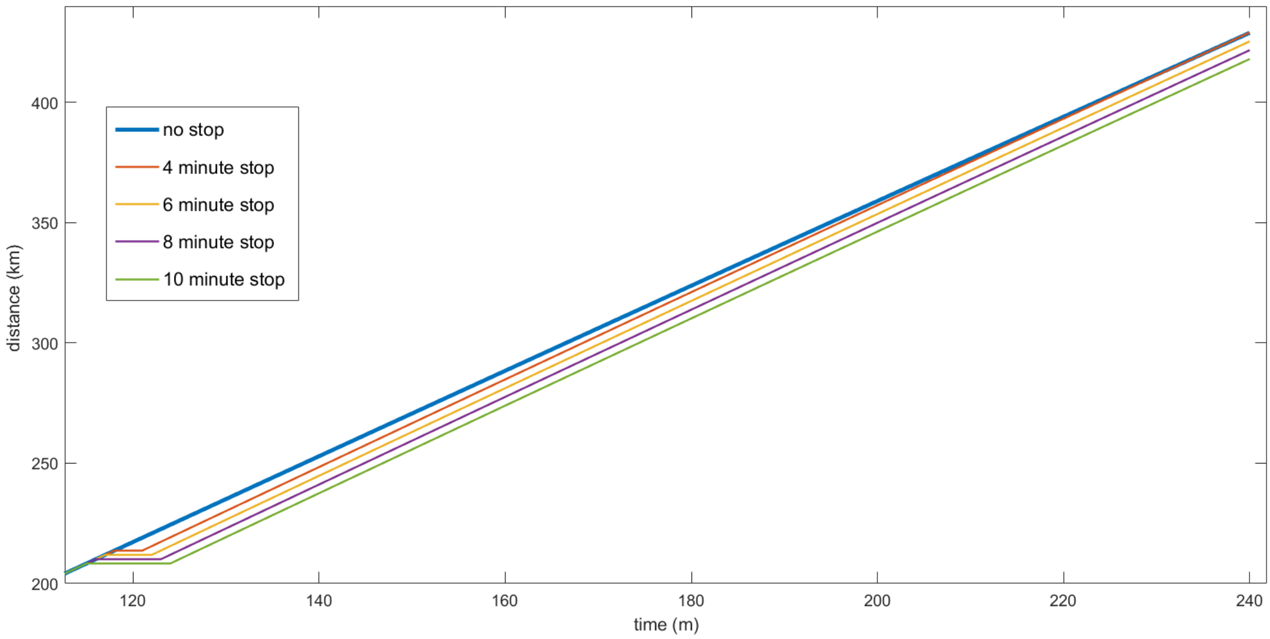


Figure A2 Payback-Period Chart for Dust Accumulation Rate = 10 $gh^{-1}m^{-2}$

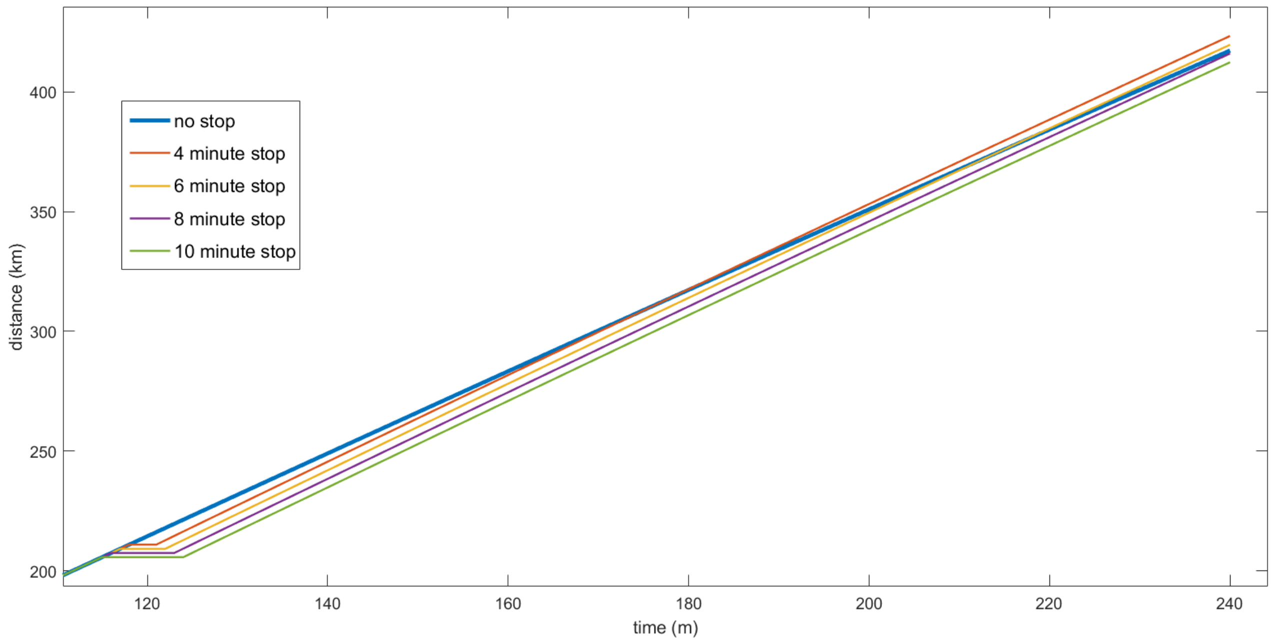


Figure A3 Payback-Period Chart for Dust Accumulation Rate = 15 $gh^{-1}m^{-2}$

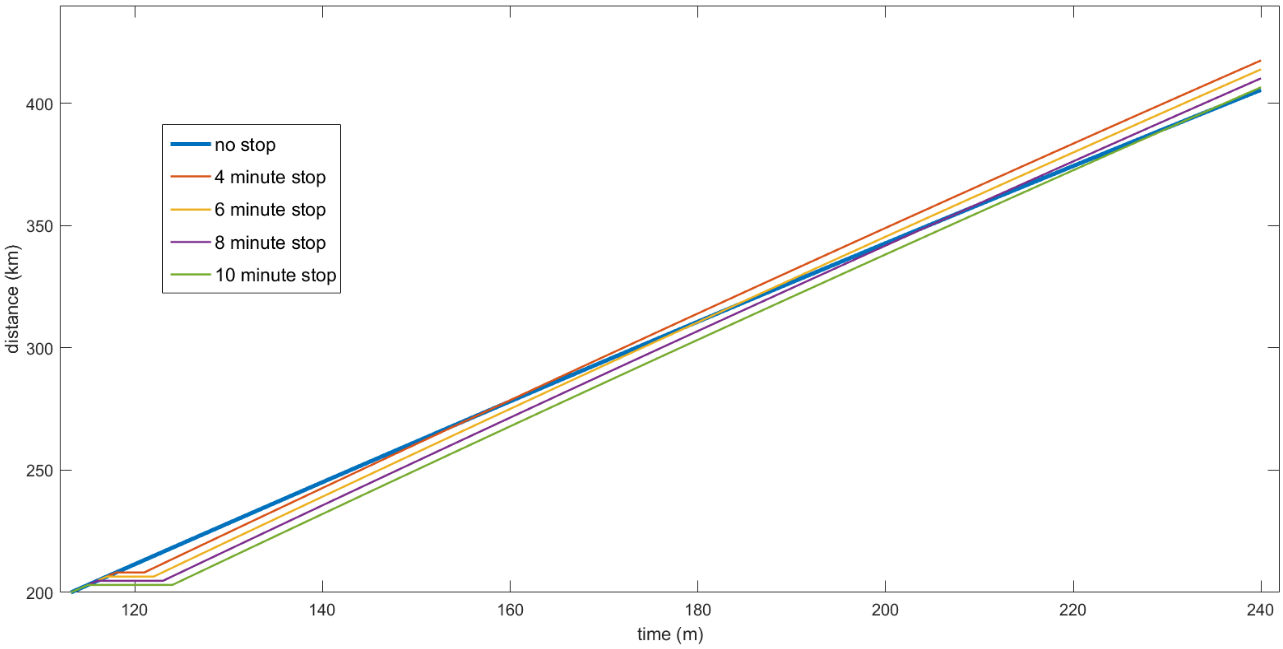


Figure A4 Payback-Period Chart for Dust Accumulation Rate = 20 $gh^{-1}m^{-2}$

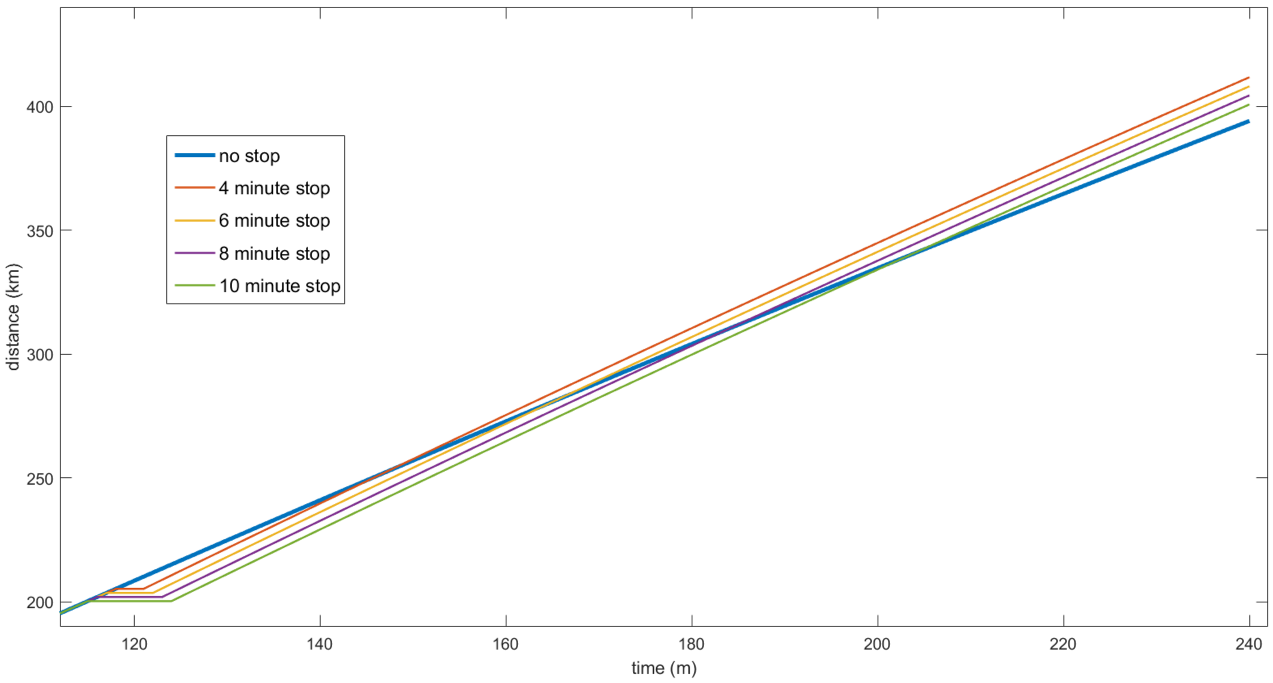


Figure A5 Payback-Period Chart for Dust Accumulation Rate = 25 $gh^{-1}m^{-2}$

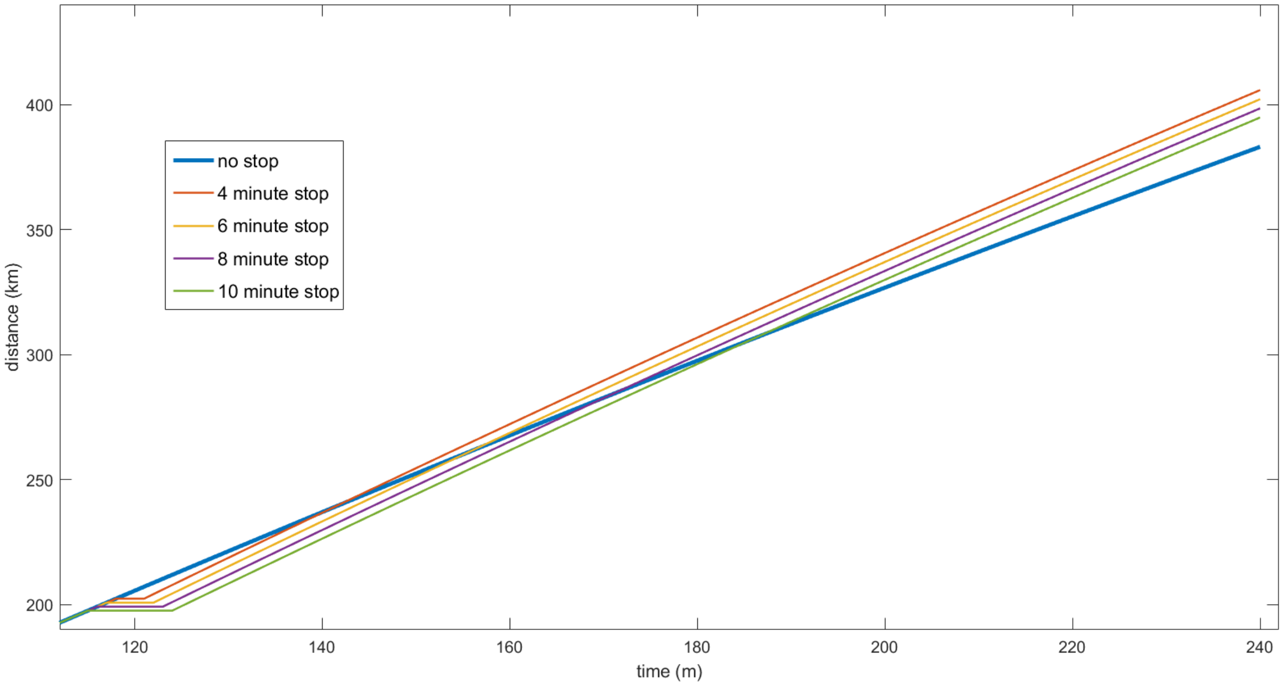


Figure A5 Payback-Period Chart for Dust Accumulation Rate = 30 $gh^{-1}m^{-2}$

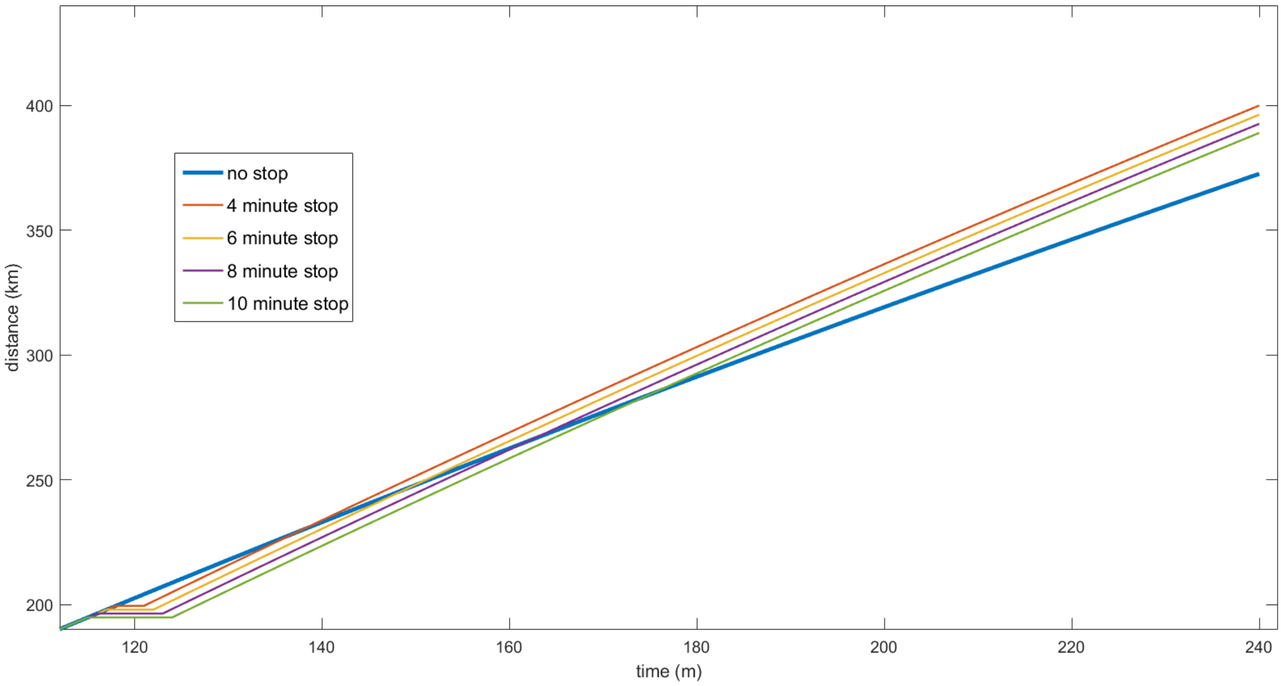
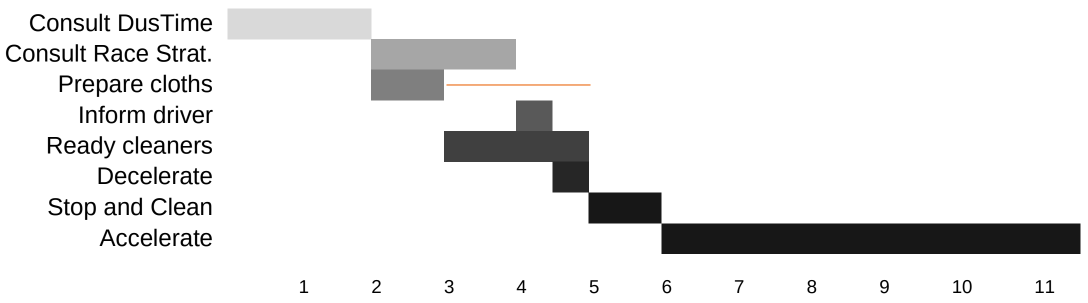


Figure A7 Gantt Chart Applied to a Short Term task with multiple Dependencies. Slack marked in orange, progression though tasks indicated by shading of grey.



MATLAB Implementation: DusTime Simulation

```
maxspeed = 110;
cleantime = 10;
simtime = 240; %minutes

stoptime = simtime/2-cleantime/2;


%interpolation data for power needed vs speed capable.
powerpc = [0,75,125,210,280,430,600,8200,1050,1375,1750,2250]/2250;
speedvec = [0,10,20,30,40,50,60,70,80,90,100,110]/110*maxspeed;

%interpolation data for dust buildup over time
timevec = [0,4]*60;
dustamount = [0,20]*4; %g/m^2   vary this for eahc different graph

%interpolation data for dust buildup vs power output
dust = [0,50,100,150,200,250]; %dust density g/sq m
powerout = [1,0.7,0.5,0.35,0.21,0.1]; %power percentage output


distancemat = NaN(simtime,4);
distance = 0;
refdistance = 0;

for time=1:simtime;
    if time>stoptime;
        if time-stoptime<cleantime;
```

```
            speed = 0;
        else
            tempdust = interp1(timevec,dustamount,time-stoptime);
            power = spline(dust,powerout,tempdust);
            speed = spline(powerpc,speedvec,power);
        end
    else
        tempdust = spline(timevec,dustamount,time);
        power = spline(dust,powerout,tempdust);
        speed = spline(powerpc,speedvec,power);
    end


    reftempdust = spline(timevec,dustamount,time);
    refpower = spline(dust,powerout,reftempdust);
    refspeed = spline(powerpc,speedvec,refpower);


    distance = speed/60+distance;
    distancemat(time,2) = distance;
    distancemat(time,4) = speed;
    distancemat(time,1) = time;

    refdistance = refspeed/60+refdistance;
    distancemat(time,3) = refdistance;
end

plot(distancemat(:,1),distancemat(:,3),'LineWidth',3);
hold on;

plot(distancemat(:,1),distancemat(:,2),'LineWidth',1.5);
xlabel('time (m)');
ylabel('distance (km)')
%legend('no stop','10m stop','20m stop','30m
stop','Location','NorthWest')

%axis([112,242,190,440])



%http://kilowatt-house.com/kilowatt-car
%http://www.sciencedirect.com.virtual.anu.edu.au/science/article/pi
i/096014819390064N
%http://www.sciencedirect.com.virtual.anu.edu.au/science/article/pi
i/0038092X9390135B
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