Analysis of the Impact of Replacing Out-dated GPS Devices in a Taxi Fleet

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Summary

GPS devices have become increasingly common due to the advancements of electronics. They can now be hand-held and are highly prominent on roads. This is particularly noticeable in taxis, as most cabs are now fitted with some form of GPS device and many fleets have enforced mandatory GPS policies. This document analyses the impact and worth of refitting a fleet of taxis the size of Canberra Cabs with new portable GPS devices. A series of systems analysis techniques were applied in the analysis of the devices in order to reduce the complexity of the components.

A major period of device improvement was identified as the time between 2007 and 2009 based on a diffusion of innovations analysis. The analysis of two particular devices, the TomTom XL 310 (2007) and the Garmin Nuvi 1350 (2009), were used as a comparative measure of the improvements made in the time period.

The devices chosen for analysis were ergonomically assessed in terms of their user interface. The major factors improved were found to be the prediction of text and consistency with other devices users may be familiar with. An experiment was then designed and performed to test these factors independently. It was found that the factors above accounted for a time saving of between 30% and 40% for acquiring the required directions on the new device.

The embodied energy of the devices was found to be approximately consistent, but other factors suggested a cheaper manufacturing process for the newer device. The environmental impact in terms of energy used in the implementation of the new devices in a fleet of taxis was then calculated as approximately 315GJ. However, based on the idling time of cars that would be saved due to the improved efficiency of new devices, it was estimated that there would be a net positive environmental impact just 27 days after implementation.

Based on a model proposed, the installation process was determined to be optimised as a 5 channel system. The cost of the installation process using this system was calculated as approximately $48500. The total cost of the devices and the savings projected due to saved time were then used to calculate the payback period of the implementation process. It was found that the installation would be financially beneficial at some point between 30 and 44 days after installation.

Based on the analysis, it was strongly suggested that all out-dated GPS devices be replace.

Contents

1. Introduction

1.1 Portable GPS Systems for Automobiles

A GPS is a device which records the user's location using satellites. Due to the ever increasing efficiency of electronics, these devices have become progressively cheaper and are now essentially hand-held. (GSA 2012) This has paved the way for a prominent market in portable GPS devices in automobiles (PGPSDAs). (GSA 2010) They allow drivers to navigate unfamiliar roads with far greater confidence and now with further developments can offer other benefits such as traffic updates and speed camera notifications. For these reasons they are particularly useful to taxi services. Other factors have contributed to the fact that most cabs now required to be fitted with some form of GPS device. (Department of Territory and Municipal Services 2010) They also allow tracking of fleet vehicles to optimise the service of customer requests. (MTData 2012)

1.2 Systems Analysis

Systems analysis is part of the systems approach to engineering. Systems analysis aims evaluate the overall design and efficiency of a system from a holistic range of considerations. The two major groups that these considerations fall under are economic factors and technical factors. (Blanchard 2013) These factors contain a large variety of sub-factors which can be analysed using a variety of techniques. The systems approach also allows the analyser to consider many hidden aspects of the system which may not otherwise be identified. In this document, a systems approach to the analysis is taken. This allowed the complex aspects of the devices to be considered in a simple way.

1.3 Aim of Analysis

The aim of the analysis presented was to determine both the environmental and financial impact of replacing out-dated GPS devices in a fleet of cabs. Only portable devices are considered in this analysis, not in-build devices. The Canberra Cab fleet was considered as an example.

1.4 Method

The analysis was performed by first determining a suitable time period over which to analyse the improvements of devices. Two devices were then used to analyse important aspects of the systems such as useability and materials consumption. The devices used for comparison were the TomTom XL 310 (2007) and the Garmin Nuvi 1350 (2009). From the analysis of these devices, the environmental and financial impacts were investigated.

2. Time Frame for Device Comparison

Diffusion of innovations analysis aims to examine the adoption rate of a given technology amongst consumers. Technology diffusion is generally described by an S-shaped curve. (Bowden, M 2004)In the context of technology adoption, an S-shaped curve is a graph of the cumulative portion of people who have adopted a technology over time. By looking at the diffusion, the maturity of a technology can be extrapolated. (Bowden, M 2004) Once a technology has matured, further efforts to improve the technology yield diminishing rewards. (Bowden, M 2004) In order to analyse the diffusion rate of PGPSDAs, market data showing the number of worldwide shipments of devices was used.

The diffusion rate of GPS devices in Australia is assumed to follow that of North America and the European Union. North America and the European Union follow similar shipment patterns in terms of proportional increase by year. Australia can be assumed to follow the same trend due to an agreement to share resources for civilian GPS devices between Australia and the USA. (GPS.Gov 2013) The agreement was made in 2007 which corresponds with the beginning of a major increase in shipments of GPS devices to North America. (GSA 2010) From this information it can be seen that Australia was enabled access to the same resources as North America a time of rapid growth. This validates the assumption that the diffusion rate will be approximately the same between Australia and North America.

To investigate the diffusion rate of PGPSDAs the number of shipments for all automobile-based GPS devices was first investigated. Figure 2.1 shows the approximate number of GPS devices for automobiles shipped to North America between 2006 and 2012, as well as a prediction of shipments in 2014 based on a GNSS device market report. (GSA 2012) The data resembles the derivative of an S-shaped curve, suggesting that an S-shaped diffusion curve is valid for GPS devices for automobiles. The derivative is expected since the data represents the rate of diffusion. The data shows that shipments peaked in 2012 and are expected to begin to slowly decrease. This suggests that transition between the early adoption phase and late adoption phase for GPS devices in automobiles occurs somewhere between 2012 and 2014. Furthermore, this suggests that GPS devices are reaching maturity.

Since an S-shaped curve was validated for the diffusion of GPS devices in automobiles, it was assumed that the diffusion of PGPSDAs specifically also follows an S-shaped curve. If the number of worldwide shipments of PGPSDAs is considered, it can be seen that the number of devices shipped peaked in 2009 and has dropped each year since. (GSA 2013) This suggests that PGPSDAs reached maturity around 2009-2010.

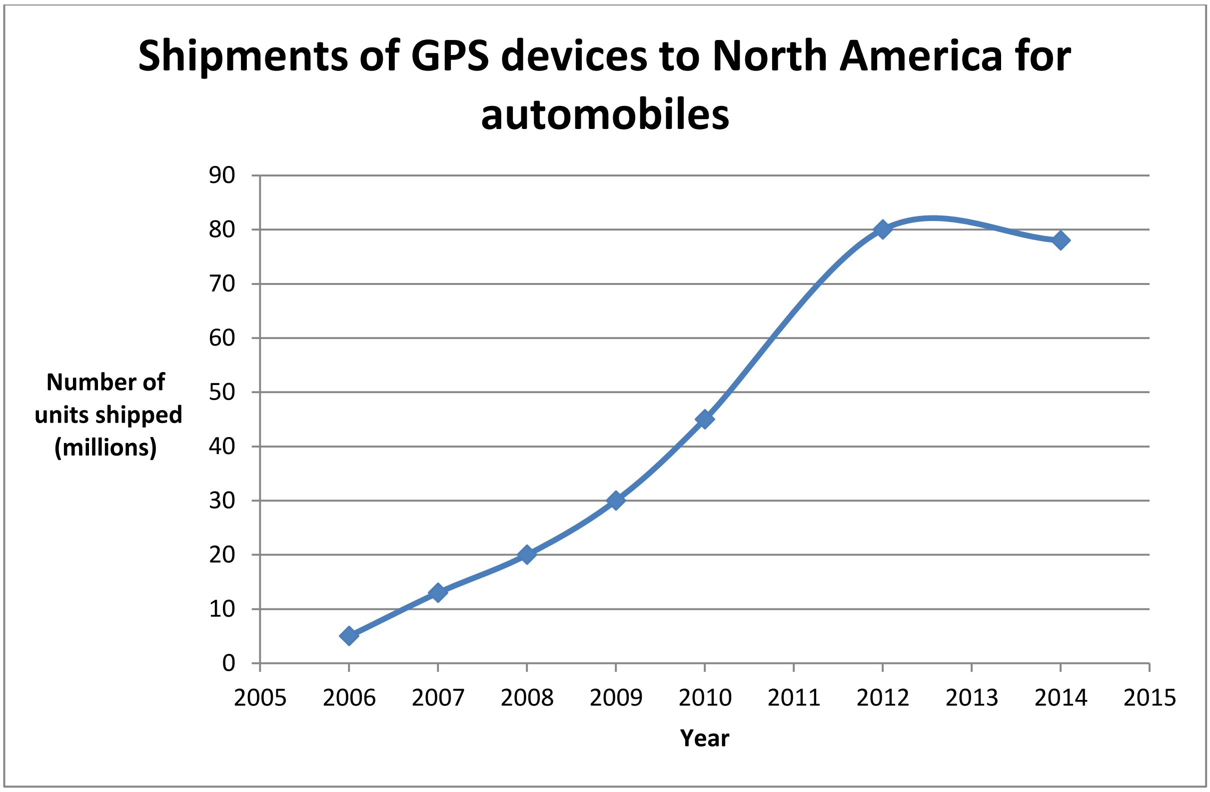

Figure 2.1: The number of GPS devices shipped to North America for automobile use according to GSA.

Based on the observations above, it can be determined that one of the major growth periods for PGPSDAs was between 2007 and 2009. For this reason, the time frame for the comparison of PGPSDAs was chosen to be 2007 to 2009. Devices beyond 2009 were assumed to not have significant improvements due to the maturity of the technology.

3. User Interface

3.1 Key changes to interface

Ergonomics looks at the comfort of a system when it is in use; an ergonomic system should be easy and simple to use. In the case of PGPSDAs, the user interface can be considered a major factor in the device's for ease of use. The change in user interfaces was investigated by comparing the two devices GPS devices. The potential impact of these changes on a taxi fleet was then considered.

The user interface of both of the devices was compared to the Apple Computer's Human Interface Principles. (Apple Developer 2013) The relevant principles for GPS devices are show in table 3.1. Principles such as direct manipulation and feedback were not considered as neither GPS device utilizes them due to restrictions on the devices. The overall aesthetics of the map displays was added as a factor for comparison as it was determined to be an important factor in the user interface. If a user is uncomfortable viewing the directions on the map, they would be more likely to become lost or panicked if they were in an unfamiliar location.

In order to compare the design principles between the devices, a survey of ten participants was taken. The participants were given the both devices simultaneously and the criteria and were asked to score each on a scale of 1 to 5. The median score of each design principle for each device is shown in table 3.1. Of the participants, five were aged 20-35, three were aged 35-50 and two were older than 50. Also, four of the participants were female and six were male. This distribution of participants was chosen in order to try to imitate the likely users or GPS devices, particularly in taxis.

From table 3.1 it can be seen that the main points of differentiation between the system interfaces are Colour Indicators, Prediction of Text and Consistency with Other Devices. These three factors account for 7 out of the 9 total point differences. This is consistent with the Pareto principle since 33% of the factors accounted for 70% of the total difference between the devices. Based on feedback from survey participants, the main inconsistency of the 2007 model with other devices was determined to be the lack of a QWERTY keyboard for input. Feedback also suggested that the prediction time of the 2009 model was much quicker.

The test only analysed the difference in the process of beginning of getting direction. That is, it shows how the different devices compare in terms of getting from the home screen to beginning directions. This is the most important aspect of a PGPSDA for a taxi driver. A comparison of directions was not considered since map and route updates are available for all devices. Hence, as long as maps are kept updated, the only differentiating factor in directions will be map provider which is dependent on the brand of the product. A comparison of verbal directions was not considered since these will also be covered in updates and new voices can be chosen.

Table 3.1: Summary of survey results for the Apple Human Interface Principles relevant to GPS devices. Note that the median scores are displayed.

Design Principles	**2007 device**	**2009 device**
Utilizes whole screen	5	5
Use of visual indicators	3	4
Negative space	2	3
Colour indicators	2	4
Prediction of Text	2	5
Use of borderless buttons	5	5
Legible font	4	4
Consistency with other devices	3	5
Map aesthetics	3	4
Total Score (out of 45)	**29**	**39**

3.2 Testing the effect of key factors

Design of Experiment (DoE) is a method of designing tests in order to isolate the effect of varying key factors. Based on the analysis of the difference in the ergonomics of user interfaces shown above, the key factors were isolated. This allowed for the formulation of a test to determine the effect that varying these factors has on the time taken to obtain directions.

The test aimed to determine the approximate time difference these prediction and consistency factors were responsible for in obtaining directions. The test involved timing the time taken for participants to obtain directions to predetermined locations both by street address and by point of interest searches. The effect of colour indicators was ignored as it was determined to be too difficult to isolate. This is because there is no way to search on the devices using only indicators, so the prediction and consistency factors would have large effects.

Consistency with other devices was isolated by choosing participants who had used PGPSDAs other than the ones being tested or regular users of computers. Also, locations which would not be prompted in predictions were chosen to remove prediction as an influential factor. These criteria were chosen due to the main inconsistency being the lack of a QWERTY keyboard for input. The results for the consistency test are summarised in table 3.2.

Prediction of text was isolated by performing the tests on participants who did not use computers or other PGPSDAs on a regular basis. Also address-based locations were given to utilize the predictability. These criteria were chosen so that there would be no predefined bias towards a given input method. The results for the prediction test are summarised in table 4.2.

Table 3.2: Average time taken to get directions for the consistency test (full results in appendix A).

	Participant 1		**Participant 2**	
Model	**2007**	**2009**	**2007**	**2009**
Average time to get directions (s)	68.7	45.7	66.5	46.7

Table 3.3: Average time taken to get directions for the prediction test (full results in appendix A).

	Participant 3		**Participant 4**	
Model	**2007**	**2009**	**2007**	**2009**
Average time to get directions (s)	34.0	21.3	38.5	24.8

The results from the tests suggest that both of the factors have a significant effect on the time taken to get directions. The tests suggest that each factor accounts for a 30-40% time difference when isolated. This shows that the time taken to get directions on newer devices should be significantly lower than older devices. These factors may have also contributed to the increased adoption rate observed in the time frame tested.

To ensure that the variation in times taken was not due to the brand of the device, professional reviews were used for comparison. A comparison was made between the 2009 device tested in the above experiment (Garmin Nuvi 1350) and an upgraded model of the 2007 device tested above (TomTom XL 340). The review gave the Garmin a 95/100 for ease of use and gave the TomTom a 91/100 for ease of use. (Gallagher 2009) Although the Garmin scored marginally higher, this does not justify the 30-40% variation observed in the experiment. This suggests the majority of the variation in time in the experiment was due to the factor tested.

The results from the tests above suggest that improvements to the user interfaces of PGPSDAs may reduce the environmental impact of a fleet of taxis. Having an improved user interface reduces the time taken to get directions which would reduce the idling time of the car. This idea is justified in section 4.3.

4. Environmental Impact of Replacement

A life-cycle audit aims to determine the impact of a product over the course of its lifetime. For most consumer devices, the embodied energy is a good indication of the environmental impact of the product. The embodied energy of two PGPSDAs was calculated in order to compare how the impact of devices evolved between 2007 and 2009. This was then used to determine the environmental impact of Canberra Cabs replacing out-dated devices with mature devices.

4.1 Embodied Energy

In order to calculate the embodied energy, a materials inventory was first performed for the two devices. Pictures of the disassembled devices are shown in appendix B. The materials inventory revealed that the 2009 device was approximately 14% light than the 2007 device. It also revealed that the newer device was much simpler to disassemble. These observations suggest that the newer devices would have a cheaper manufacturing process as they require fewer materials and are easier to assemble, allowing an increased production rate. A cheaper manufacturing process suggests a cheaper overall product which is consistent with the increased adoption rate observed between 2007 and 2009.

To calculate the embodied energy of the two devices, it was assumed that the embodied energy of components was the same as similar components for smartphone production. Values for these components were obtained from WattzOn and are shown in appendix C. The embodied energy of PCB general material was calculated by scaling the embodied energy of an iPhone PCB. The embodied energy of plastic, aluminium and glass were also obtained from smartphones. The embodied energy of rubber and steel was assumed to be the same as that for a computer. Both of the lithium ion batteries were assumed to have the same embodied energy due to a minor weight difference between them.

The life-cycle assessment presented does not include the embodied energy of transportation or disposal. These factors were omitted because they were assumed to be similar. This is justified by the observation that the devices are made in Asia and contain similar components. The likeness of the embodied energies of transportation and disposal between different smartphones also supports the assumption that the factors would be similar between the two devices. For the population impact, the transport and disposal energies were considered to be the same as for an iPhone.

Based on the assumptions above, table 4.1 and table 4.2 suggest that the embodied energy of the 2007 device and the 2009 device are approximately equivalent. There is only a 6% difference between the embodied energies of the materials of the devices which is negligible considering the assumptions made in the calculations.

Table 4.1: Materials inventory and embodied energy (Wattz On 2009) for the TomTom One XL (2007).

Component type	**Component**	**Material**	**Weight (g)**	**Embodied energy (MJ)**
Electronics	PCB	PCB general	24.47	798.7
	Screen circuit	PCB general	3.24	105.7
	Speaker	Other	21.07	2.107
Casing	Outer Frame	Plastic	4.09	0.409
	Case	Plastic	34	3.4
	Dust protector	Rubber	8.33	0.7113
	Inner Frame	Aluminium	8.80	1.627
	Screws	Steel	0.69	0.3012
Other	Battery	Lithium ion	23.68	88.98
	4.3’ Screen	Glass	60	1.335
		Total	**189g**	**1003MJ**

Table 4.2: Materials inventory and embodied energy (Wattz On 2009) for the Garmin Nuvi 1350 (2009).

Component type	**Component**	**Material**	**Weight (g)**	**Embodied energy (MJ)**
Electronics	PCB	PCB general	24.55	801.31
	Screen circuit	PCB general	1.74	56.76
	Speaker	Other	2.99	0.30
Casing	Outer Frame	Plastic	2.64	0.26
	Case back	Plastic	25	2.50
	Case Front	Plastic	8.17	0.82
	Screen case	Aluminium	24.35	4.50
	Screws	Steel	0.62	0.27
Other	Battery	Lithium ion	21	77.86
	4.3’ Screen	Glass	52	1.16
		Total	**163 g**	**946 MJ**

4.2 Total energy

The data above can be used to determine the environmental impact of replacing all of the PGPSDAs in Canberra Cab fleet. Canberra Cabs has a fleet of 333 cabs which was considered to be the population when looking at the environmental impact. (Canberra Airport 2011)

It was assumed that the process of replacing the devices in the fleet instigated the production of the devices. Hence, the energy used in the process was considered to be the embodied energy of the new device, the transportation of the new device and the disposal of the old device for each cab in the fleet. The transportation and disposal energies were approximated as the same as for an iPhone. These values are shown in appendix C.

Based on the assumption about the transportation and disposal and the data in table 4.2, the embodied energy of the replacement process for each was estimated to be 947 MJ. This equated to a total population consumption of 315 GJ for the entire Canberra Cab fleet replacement.

4.3 Payback period of embodied energy

Gasoline contains approximately 33.4 MJ/L of energy and a typical internal combustion engine has a thermal efficiency of approximately 25%. (Alternative Fuels Data Centre 2013) (Yates, Z 2002) An idling vehicle uses approximately 1 L of fuel every 15 minute. (Consumer Energy Centre 2013) Using this information it was calculated that the power consumed by an idling vehicle is approximately 8.9 MJ/minute. Hence, in order to repay the embodied energy of the installation of the new devices, it would take a saving of approximately 589 hour of idling of vehicles. It is shown in section 4.2 that it can be assumed that the new devices save approximately 10 seconds per trip in idling time. If this is considered, then it would take about 212200 trips to repay the embodied energy of the device installation. This equates to approximately 637 trips per cab in the fleet. It is not unreasonable to assume that a cab can make 24 trips per day if an average trip time of 15 minutes and a working day of 8 hours are assumed. Then the payback period for the embodied energy of the replacement process can be calculated to be approximately 27 days. A payback period of 27 days shows that rather than having a negative environmental impact, the installation of new devices may well be beneficial.

Though this is a very rough estimate, it suggests that the payback period is in the order of days or months, rather than years which suggests a positive impact. It should also be noted that this estimate was made without considering the energy required to obtain the fuel, which would only reduce the payback period.

5. Financial Impact of Replacements

If a proposal for new PGPSDAs to be fitted in a fleet of taxis was to be considered, perhaps the most influential factor would be the financial impact of the installation. The payback period for both the purchase and installation of new devices was considered.

5.1 Cost of Installation

Queue theory can be used to determine holding times for a service and optimize the number of channels in a design. In the context of PGPSDAs, the service was considered to be the installation process and the number of channels was considered to be the number of workers needed to install the devices. The service rate was estimated in order run a simulation to determine how the optimum number of channels to use for the installation.

To investigate the average waiting time for the installation of a GPS in a cab in the Canberra Cab fleet the following assumptions were made:

- The cab service would like the implementation complete in all cabs within a two week period.
- The cabs will be taken off the road according to a Poisson distribution due to uncertainty as to when they will have fewer customers.
- The cabs will be taken off in two groups each day and each group must be completed within a 4 hour period.
- Once a cab is fitted with a device, it can return to duty.
- Each device will take 1 hour for installation. This includes testing time for the devices.
- The wages of the installers and the cab drivers follow the Australian national average of $36/hour.
- Each cab makes, on average, three 15 minute trips each hour.

The time taken to install the devices was estimated based on the experiences of the author who installed four different PGPSDAs, but was made conservative to allow for testing of the devices. The assumption of a Poisson distribution is due to the randomness of when cabs will be taken off the road. It was assumed that this will be done according to when there are be fewer customers during the day, so is dependent on the random nature of people. The four hour service period was chosen to accommodate an 8 hour working day and to allow the vehicles to go back on to the roads once installation was complete. The assumption that each cab makes three 15 minute trips each hour was chosen to reflect the time in which the taxi is not serving a customer and hence not making income. Based on data from the Canberra Cabs website, each 15 minute trip would generate approximately $40 in revenue for the company. (Canberra Elite 2010) Installer and cab driver wages were estimated as approximately the Australian average since this is the best estimate which could be made. (ABS 2013)

Based on the data and assumptions above, the parameters of a multiple channel queue theory analysis were determined to be:

- Time period (T): 4 hours.
- Expected arrivals per period (λ): 12.
- Expected service completions per period per channel (μ): 4.
- Number of channels (*c*): variable to be optimised.

Using these values, a Matlab function was developed to simulate the total cost of implementation for different numbers of channels. The function used queue theory equations for a multiple channel single phase system to estimate the average holding time for a cab in the queue. The script for the function is attached in appendix D. Figure 5.1 shows the simulation results for the number of channels between 4 and 9.

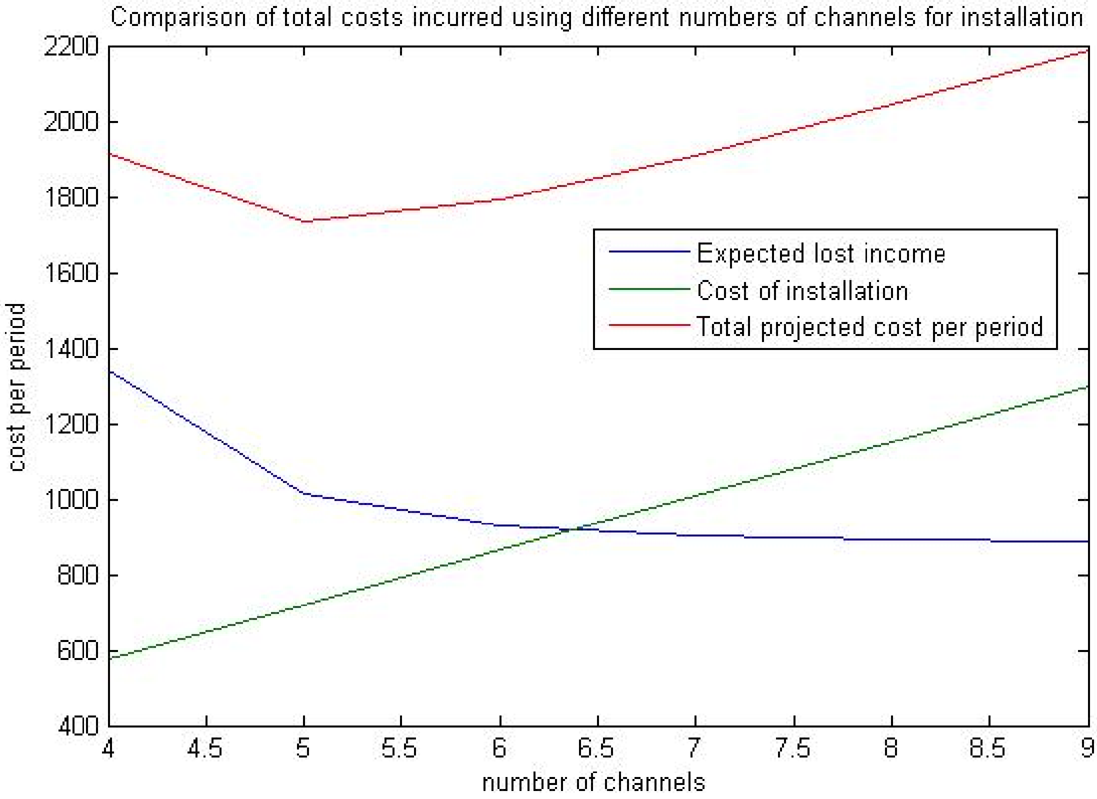

Figure 5.1: Simulation results for testing how different numbers of channels would affect the total cost of implementation.

From figure 5.1, it can be seen that based on the model presented, the optimum number of channels to install new PGPSDAs in the Canberra cab fleet is 5 channels. When a 5 channel system is used, the total cost of implementation is minimised at $1732 per time period. Since 28 time periods are needed to fit the entire fleet with a new device, the total cost of implementation cost would be approximately $48500.

This analysis is based on a very simple model. To reduce the total cost, a more complicated model where services may be performed when fleet vehicles are not in use could be considered. However, data on the number of taxis not in use on different days and at different times of day could not be obtained. An improved model may also consider penalty rates for the installers and the proper wages of cab drivers. The number of installations per time period may also be determined more accurately.

5.2 Payback period of implementation

A payback period is the time taken for an investment to pay itself off in the savings that it generates. To determine whether the implementation of new devices is worthwhile, a payback period was calculated for replacing Canberra taxi GPS devices. The average price of a device was used in the calculation, as well as the installation cost calculated above.

The average cost of a device was taken to be $180. This number was decided based on the average prices in the catalogues of The Good Guys and JB Hi Fi retailers. (The Good Guys 2013) (JB Hi Fi 2013) This number was verified as being reasonable from the GSA 2012 market report for GNSS devices. (GSA 2012)

The savings from the implementation of new devices were considered as the time saved in searching for a location on the device. Due to map updates, the routes taken were assumed to be equivalent regardless of the device used. By assuming that cab drivers would search by address and based on the data determined in the section 4.2, it was conservatively approximated that there would be a saving of 10 seconds for each 15 minute trip. Hence, if the new devices are installed, there will be an increased capacity of 1 trip for each 90 trips with the old devices. There is a loss involved with the time saving, in that each customer will pay less for their trip since it will be slightly quicker. However, the time saving allows more customers to be serviced, so the time spent driving with a customer was assumed to be equivalent with both the new and old devices. This means that the only difference would be an extra flag fall charge in each 90 trips. The flag fall charge for a cab in Canberra is $7. (Canberra Elite 2010) This equates to an increased profit of $7 for each 90 trips with the old devices. Using this information, it was determined that the increased profit is $0.31 per hour of customer service per cab.

Another contributing factor to the payback period of new devices is the fact that most new devices offer free map updates to users. The updates for old devices generally cost approximately $100. (Garmin 2013) (TomTom 2013) These updates are released every three months by major GPS companies. (Garmin 2013) (TomTom 2013) The payback period was considered in a scenario where the old devices are updated at the time when the new devices would be installed and also without any updates. Figure 5.2 shows the costs for scenario where updates are not installed in the old device. Figure 5.3 shows the costs for the scenario where the old devices are updated.

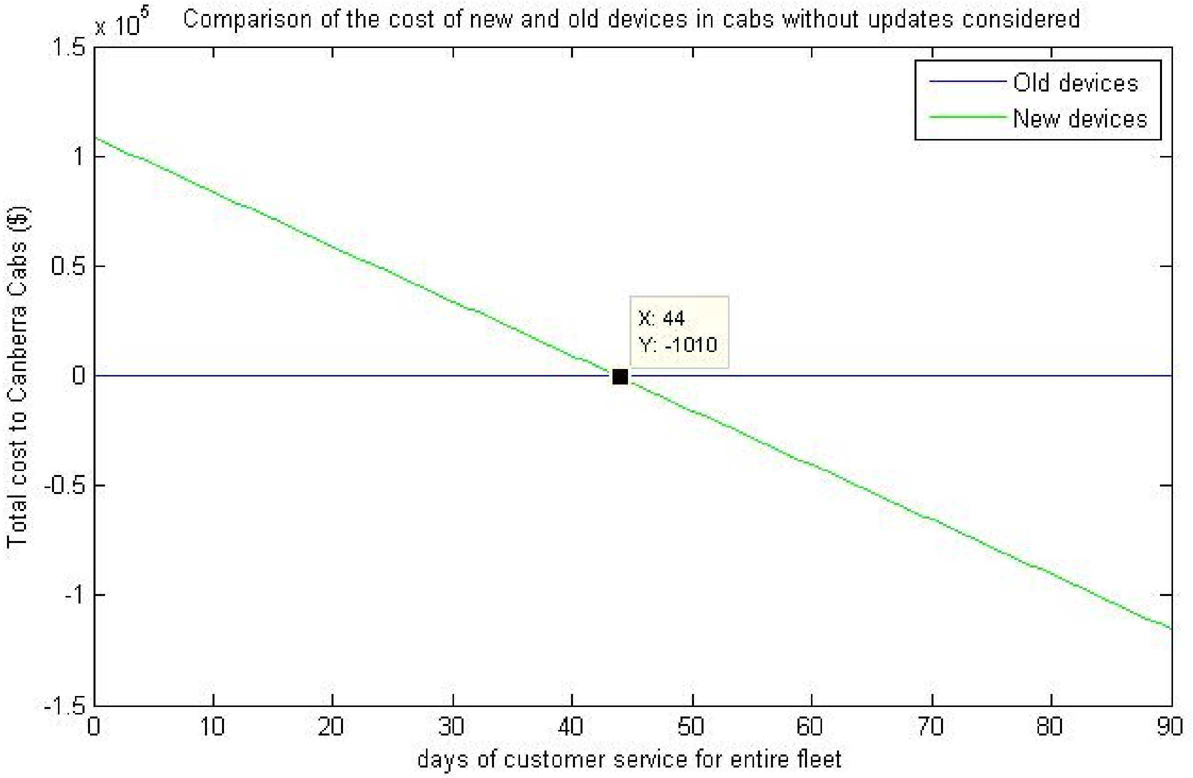

Figure 5.2: The cost to the fleet with old devices compared with the new devices without considering an update to the old devices.

Figure 5.2 shows that the payback period when updating old devices is not considered is 44 full days of customer service by the entire fleet. Hence the payback period depends on the average amount of time each cab is actively serving customers per day. For example, if the average amount of customer service time for a cab is 6 hours per day, the payback period would be 176 days.

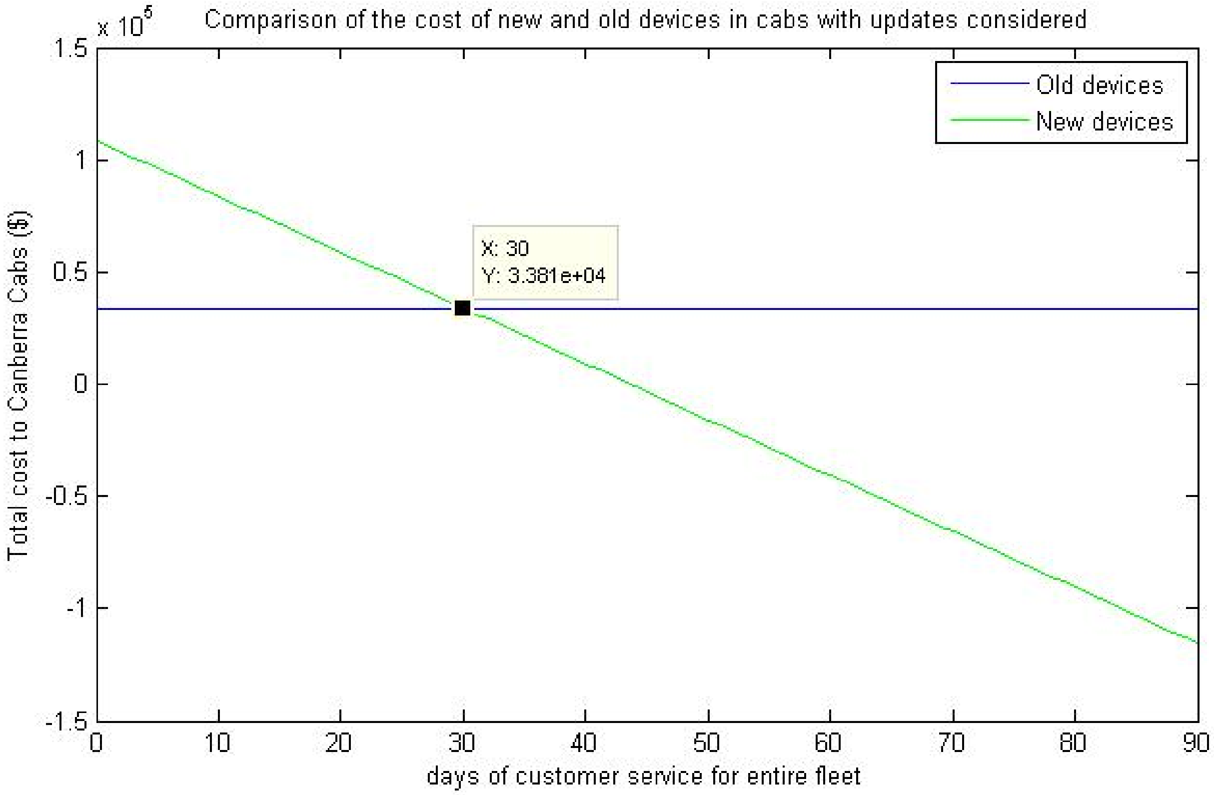

Figure 5.3: The cost to the fleet with old devices compared with the new devices if the old devices are updated.

From figure 5.3 it can be seen that the payback period when the old devices are updated is 30 days of customer service by the entire fleet. If the example of the average amount of customer service per cab per day is considered again, the payback period in this scenario would be 120 days.

It is also interesting to note that from the figures above, it can be seen that the implementation of new GPS devices acts as a linear investment. This observation suggests that periodic replacement of the devices would produce even further savings. These savings would be dependent on the rate at which the main problems with GPS devices improve. If predictions about the rate of improvement of devices were made, the optimal rate at which to replace the devices could be determined.

The additional cost of disposing of the old devices was not considered in this analysis and could have an impact on the calculation.

6. Conclusions

The analysis revealed that the replacement of old devices in a taxi fleet the size of Canberra Cabs is likely to yield positive impacts from both a financial and environmental perspective. The diffusion rate of portable GPS devices for automobiles suggested that a suitable time frame for comparison of devices between the improvement and maturity stages was between 2007 and 2009. Using this time frame, two devices were compared to assess improvements which have been made to devices. The main aspects considered were the user interface and the materials consumption. An experiment revealed that the user interface 2009 device was found to perform significantly better than the 2007 device, allowing for a reduction of between 30% and 40% in time taken to obtain directions in all participants. It was also found that the 2009 device is likely to be cheaper to manufacture, but the embodied energy of the devices could not be definitively differentiated. From these improvements it was determined that the replacement of old devices with new ones may well yield a positive environmental impact, with estimates suggesting a 27 day payback period on the energy consumed for the production, transport and disposal of necessary devices. A model of the installation process of new devices suggested a 5 channel system was the most financially efficient. Based on this model and general retail cost of devices, a payback period of between 30 and 44 days was determined.

Based on this analysis, the upgrade of out-dated GPS devices in cabs should be strongly recommended as it yields both financial and environmental benefits.

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Appendix A: Test results for the user interface tests

Table A.1: Time taken to get directions for the consistency test.

	Test 1		**Test 2**	
Location	**2007**	**2009**	**2007**	**2009**
Turkish Pide Gungahlin	74	32	62	44
Melba District Playing Fields	40	41	51	45
Hawker bakery	54	62	59	48
Watson takeaway	82	69	61	42
Kambah Caltex	51	28	72	41
Woolworths Weston	111	42	94	60
Average	**68.7**	**45.7**	**66.5**	**46.7**

Table A.2: Time taken to get directions for the prediction test.

	Test 1		**Test 2**	
Location	**2007**	**2009**	**2007**	**2009**
33 Hibberson Street	33	24	40	25
Brownlee Place	34	21	35	27
38 Hawker Place	39	20	33	23
3 Watson Place	30	18	36	23
3 Marconi Crescent	35	22	46	25
26 Brierly Street	33	23	41	26
average	**34.0**	**21.3**	**38.5**	**24.8**

Appendix B: Pictures of materials audit

Figure B.1: The components of the TomTom XL 310 (2007).

Figure B.2: The components of the Garmin Nuvi 1350 (2009).

Appendix C: Embodied energies

Table C: The embodied energy of materials found in the GPS devices in the materials inventory.

Material	**Embodied energy (MJ/Kg)**
PCB general	32600
Plastic	100
Steel	32
Lithium ion	3700
Glass	22
Other	100

Note that these values were references against two sources (WattzOn 2009) (Victoria University of Wellington) where possible.

Embodied energy for the transportation of an iPhone: 0.5MJ (WattzOn 2009)

Embodied energy for the transportation of an iPhone: 0.013MJ (WattzOn 2009)

Appendix D: Equations and code for channel optimisation

Matlab code:

```
%Title: waiting time for queue theory
%Author: Samuel Stefopoulos
%Date last modified 23rd October 2013

%This function calculates the average service time for a given number of
%channels based on the expected arrivals per period and the expected
%service completions per period.

function [T] = waitingTime (c)

%expected arrivals per period
L = 12;

%Expected service completions per period
u = 4;

%Installer wages ($) per period
Ci = 144;

%Expected income ($) from each cab per period
Cc = 296;

%Components of P_0,0 calculation
p1 = (L/u).^c;
p2 = 1./factorial(c);
p3 = 1./(1-L./(c.*u));
p4 = 0;

%compute p4
for (r = 0:c-1);
    p4 = p4+((L/u).^r).*(1/factorial(r));
end

%P_0,0 Calculation
P = 1./(p1.*p2.*p3+p4);

%Components for length of queue calculation
m1 = (L/u).^(c+1);
m2 = factorial(c-1);
m3 = (c - L/u).^2;

%average length of queue
m_m = P.*m1./(m2.*m3);

%Mean waiting time in queue
w_m = m_m/L;


%Holding time in queue
T = w_m+1/u;

%Plotting the curves to show costs
plot(c,T*L*Cc,c,c*Ci,c,T*L*Cc+c*Ci);


xlabel('number of channels'); ylabel('cost per period'); title('Comparison of
total costs incurred using different numbers of channels for installation');
legend('Expected lost income', 'Cost of installation', 'Total projected cost per
period');

end
```

Equations for a multi-channel queue: (Blanchard 2011)

λ = expected arrivals per time period

μ = expected service completions per period

c = number of channels

The probability that there are no units in the queue and no channels are occupied:

$$P_{0,0} = \frac{1}{\dfrac{1}{\left(1-\dfrac{\lambda}{c\mu}\right)}\left(\dfrac{\lambda}{\mu}\right)^{c}\left(\dfrac{1}{c!}\right)+\sum_{r=0}^{r=c-1}\left(\left(\dfrac{\lambda}{\mu}\right)^{r}\left(\dfrac{1}{r!}\right)\right)}$$

The mean length of the queue:

$$m_m = P_{0,0}\frac{\left(\dfrac{\lambda}{\mu}\right)^{c+1}}{(c-1)!\left(c-\dfrac{\lambda}{\mu}\right)^{2}}$$

The mean waiting time:

$$w_m = \frac{m_m}{\lambda}$$

The mean holding time:

$$d_m = w_m + \frac{1}{\mu}$$