The Impact of Adverse Weather Conditions on Urban Bus Performance Measures – an Analysis Using ITS Technology

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Abstract— **Increases in congestion levels caused by adverse weather conditions are difficult to predict and therefore urban bus operators cannot incorporate appropriate changes into their planning, scheduling, and management decisions. Adverse weather conditions have an impact on the level of service an operator provides. They also result in higher levels of congestion due to an increase of personal car usage. The aim of the research paper is to investigate the impact of adverse weather conditions on urban bus performance measures. The Irish city which is used for this study given its geographical location experiences a maritime climate, dominated by low pressure from the Atlantic bringing cold wet weather with the trade winds. The study includes various types of performance measures such as ridership, frequency, headway regularity and travel time, which are analysed both in the presence and absence of adverse weather conditions. The performance measures include changing variables such as stage and destination, peak and off-peak, inbound and outbound in order to provide a comprehensive analysis. The data used for this research originate from an electronic fare collection system. 46 million individual boarding records are stored in the database.**

The results of the research paper include the calculation and presentation of various analysed performance measures followed by an extensive interpretation of how this information can support decision-making. The quantitative analysis method aims to improve and adjust planning, scheduling, and management decisions of urban bus operators and thereby alter and improve operations and level of service provided.

I. Introduction

INCREASES in congestion levels and changing passenger behaviour caused by adverse weather conditions are difficult to predict and therefore urban bus operators cannot incorporate appropriate arrangements into their planning, scheduling, and management decisions. Adverse weather conditions have an impact on ridership, frequency, travel time and headway regularity. They may also result in a higher level of congestion due to an increase in personal car usage.

Including weather conditions as one parameter of an analysis is very common practice. Undoubtedly adverse weather conditions have an impact on public transport passenger behaviour and public transport service performance. Car use on a rainy day is generally increased leading to higher congestion levels [1, 2]. Intelligent Transport Systems (ITS) and newest techniques for weather prediction allow for new analyses and forecasting [3]. It is only when a clear understanding of the impact of adverse weather conditions on public transport performance and passenger behaviour is reached that systems can improve, become more efficient and deliver a better service.

This paper focused on data obtained from an electronic fare collection (EFC) system and meteorological data obtained from Met Éireann, the Irish meteorological service. The EFC database contains over 160 million records. The combination of these two data sources facilitated the analysis presented in this paper.

The purpose of this paper is to investigate passenger behaviour during adverse weather conditions. If this behaviour is known, it would help in decisions relating to changing the dispatch time of buses on rainy days to increase the level of service and thus customer satisfaction. The paper further demonstrates how Intelligent Transport Systems (ITS) data can be used to infer passenger behaviour and performance measures.

The paper provides details about the project databases and a brief literature review. The methodology section describes the analysis and introduces the performance measures that are used to investigate the impact of adverse weather conditions. Each performance measure is described and the results are discussed in detail.

In accordance with a confidentiality agreement, details of the dataset cannot be presented and where route numbers etc are mentioned they have been changed.

II. Background

A. Literature Review

The impact of adverse weather conditions on the traffic flow on freeways leads to the conclusion that rainfall has a significant effect on freeway capacity and operating speed [1]. The results from Smith [1] show a reduction in capacity and operating speed. Their findings are then compared to the Highway Capacity Manual (HCM) [6]. The Transit Capacity and Quality of Service Manual (TCQSM) [7] is the equivalent of the HCM in the public transport sector. However, the impact of weather was not considered in the TCQSM. The performance measures introduced in 'A Guidebook for Developing a Transit Performance-Measurement System' [7] mentions the influence of adverse weather for some performance measures.

A study that focused on service regularity clearly acknowledges adverse weather conditions as a cause for variation in trip times, boarding and alighting times [8]. Adverse weather is further widely acknowledged as a factor that negatively influences the comfort of passengers [9, 10]. Weather conditions were also included in a study that focused on a hybrid discrete choice model which also considered the fuzziness of subjective rating data such as

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weather conditions. Experience in the United Kingdom shows that, for example, elderly public transport passengers not only travel more frequently in the summer than in the winter but they also travel more in a good summer than in a bad summer [11].

The idea of weather responsive traffic management is introduced by Pisano [2]. The study analysed the impacts of adverse weather on traffic flow and discusses operational strategies which may improve safety.

A study carried out in Eindhoven, Netherlands, investigated the key events and critical incidents influencing transport mode choice switching behaviour [12]. The survey included 115 observations. In the environment category, 43.5% of all responses indicated that a change in weather is relevant and influences their choice.

B. Project Database

The project database is based on data gathered from an urban bus operator on its entire transportation network. Wayfarer provides the EFC system that is responsible for the compilation of this data, which forms the basis of this research project. The vast amount of transactional data from 1998 and 1999 (160 million records) has been moved from text files (one file per day) into a large relational Oracle database [4]. The initial transactional data has been enriched with additional datasets (bus stop locations, spatial information, ticket types, transfer journey identification), which contributes considerably to the application, capability and usability of the system [5].

By enriching the database with meteorological data originating from records stored by the Irish Meteorological Service, Met Éireann, it was possible to investigate the impact of adverse weather conditions on urban bus performance measures. The weather station which collected the data used in this study is approximately 10 km north of the city centre. The following weather measures were included in the dataset:

- Date,
- Hour,
- Rainfall (mm),
- Temperature,
- Mean wind speed,
- Mean wind direction,
- Weather description

For the purpose of this study the focus was mainly on the rainfall measure.

III. Methodologies and Objectives

The Guidebook for Developing a Transit Performance Measurement System [9] will be used as reference to the various performance measures. The guidebook was published by the Transportation Research Board and serves transit managers in the decision-making process of improving or establishing a transit performance measurement system. The following performance measures will be used by this study:

- Ridership
- Frequency of service
- Headway regularity
- Bunching
- Travel time variability

Each of these performance measures will be applied to a set of EFC data taken from a rainy period and a set of EFC taken from a non-rainy day. Depending on the performance measure the data may be aggregated. The focus is on morning/evening peak periods as during these times the congestion levels are at their highest.

A simple two-factor definition (rain/no rain) is used to define adverse weather conditions. Apart from strong winds there are no major other adverse weather factors in Ireland due to its geographical position. Ireland has mild, wet winters and warm variable summers with frequent showers of rain. The annual rainfall is 800-1000mm. The average number of wet days (> 1mm of rain) ranges from about 150 days a year (east coast) to 225 days a year along the western coast line of Ireland.

The periods used for the analysis were unbiased by other factors such as public holidays or major events. Random factors that might have changed the travel behaviour of passengers were eliminated by analyzing the variability of the results.

All *'rainy'* days were days where it rained more than 15mm/day unless otherwise indicated.

Other commute options are only available for particular route segments. The analysed routes in this paper exclude the other commute options as alternative transport choices.

For the purpose of confidentiality it is not possible to identify the Irish city.

IV. Results

A. Ridership

Ridership is an economic measure which focuses on how well operator resources are used. The service and capacity monitoring measurement provides the public, decision makers and transit management with valuable information. Ridership is the number of passenger boardings on either a subset of the network (route, route segment) or of the entire network for a given period of time. This measure generally consists of the number of unlinked trips ignoring transfer journeys, which means that each boarding is counted. This economic measure is often needed to calculate other performance measures. For the purpose of this paper, the ridership has been extracted from the EFC database. However, the ridership only includes passengers that have validated their boarding using a magnetic strip card – cash transactions are not included as they were unobtainable for this project.

The ridership in this paper introduced the different totals not clear what you mean by 'the ridership introduced different totals' for periods where adverse weather conditions were present (rain) and when they were not (no rain). The comparisons between two ridership levels were measured on the basis of one period with rain and the same period without rain a week before or a week after (depending on the weather data). Three different periods have been analysed; morning peak (8am-9am), evening peak (4pm – 6pm) and off-peak (2pm-3pm). In addition to the three periods, a comparison of two rainy days has been made. The first rainy day was a Friday in May with a daily rainfall of 18mm (0.71") and a total ridership of 73,607. Two other Fridays in May with no rainfall recorded a total ridership of 76,559 and 81,477. The second rainy day analysed was Friday in November with a total rainfall of 20mm (0.79") and a ridership of 99,454. The following Friday (no rain) recorded a total ridership of 102,559 passengers.

Fig. 1 shows more detailed ridership data and compares rain/no rain ridership of different periods throughout the day. The general tendency shown in the charts lead to the conclusion that passengers who travel using a magnetic strip card try to find alternative modes of transport on days when it rains. It would be interesting to analyse the data of cash boardings to see whether passengers who usually do not use urban transit systems change their mode of transport when it rains. However, this is not possible with the existing database.

B. *Frequency of Service*

The frequency performance measure is an availability measure which provides the public, the decision-makers and the service planners with information on how often the transit service is provided. It is generally measured in transit vehicles per hour.

For the purpose of this study the frequency measures were extracted from the EFC database focusing on 3 different services both outbound and inbound. The frequency was extracted for morning peak, evening peak and off-peak on both rainy days and non-rainy days. After extraction of the data, several two tailed, paired t-tests were applied to compare the mean frequencies of the rainy and non rainy samples with the result that H_0 = 'means are equal' could be rejected with strong statistical evidence (95% confidence interval). The values for the two tailed, paired t-test were 0.058 (Route 1 – Inbound), 0.445 (Route 1 – Outbound), 0.882 (Route 2 – Inbound), 0.251 (Route 2 – Outbound), 0.731 (Route 3 – Inbound), and 0.223 (Route 3 – Outbound). Therefore there is a difference in means with regard to rainy days and non-rainy days. Table I shows the summary of the analysis. The trend of these results is that the average frequency of inbound journeys is higher on non-rainy days.

TABLE I: AVERAGE FREQUENCIES OF ROUTES 1-3

		Inbound		Outbound	
		Rain	No Rain	Rain	No Rain
Route 1 (buses/hour)	**Morning**	9.2	**9.8**	8.4	**8.6**
	Evening	9.8	**11.5**	9.3	**13.0**
	Off-Peak	8.0	**8.7**	8.7	7.7
	Entire Day	156.0	**167.0**	118.5	**125.0**
Route 2 (buses/hour)	**Morning**	13.2	**13.9**	6.8	6.2
	Evening	6.3	**6.3**	8.0	7.5
	Off-Peak	6.2	**6.3**	6.8	6.0
	Entire Day	150.0	**152.5**	110.0	**122.0**
Route 3 (buses/hour)	**Morning**	5.8	**6.2**	6.8	5.8
	Evening	5.8	4.0	9.3	7.3
	Off-Peak	4.7	**5.0**	7.0	**7.5**
	Entire Day	88.5	**89.0**	116.0	**116.0**

***** Grey areas show when the average frequency was higher on non-rainy days.

This also applies for the average daily frequencies (inbound and outbound). Route 1 is mostly a city centre route whereas routes 2 and 3 connect suburban areas from the north and south with the city centre which may explain the variances of results of rainy and non-rainy days. Routes 2 and 3 also take advantage of quality? bus corridors providing a more constant flow and adverse weather may have less influence. Headway and bunching could also bias the results.

C. *Headway and Headway Regularity*

Headway regularity is a reliability performance measure for buses at a stop, route or system level. Analyses such as service regularity, headway adherence, assessment, headway ratio and headway deviation can be carried out to provide information for the public, decision-makers and transit management. Although the service regularity is often measured by comparing the actual with the scheduled headway, this study is only interested in comparing the actual headway on a rainy day with the actual headway on a non-rainy day. A headway regularity index exists [13]. High index numbers indicate a regular service whereas low numbers indicate headway irregularities. The formula is as follows [13]:

$$R = 1 - 2\sum_{r=1}^{n} \frac{r(h_r - H)}{n^2 * H} \qquad (1)$$

where

R Headway regularity index

r	rank of headways – 1….n
n	total number of headway measures
h_r	series of headways
H	mean headway

When the headway measures are equal for n observations, then the headway regularity index will be 1. The larger the differences between the observations the smaller will be R. The headway regularity index was calculated for three routes in different directions on rainy and non-rainy days. The results are shown in Table II and Fig. 2. It seems that there is a noticeable trend towards higher headway regularity on rainy days. This is true for all but one observation. The average service regularity for the three routes is 0.668 and 0.633 for rainy and non-rainy days respectively.

TABLE II: HEADWAY REGULARITY INDEX

Route	Inbound		Outbound	
	Rain	No Rain	Rain	No Rain
Route 1	0.58	0.55	0.64	0.59
Route 2	0.46	0.62	0.75	0.73
Route 3	0.76	0.58	0.82	0.73

* Grey areas show when the headway regularity was less on non-rainy days.

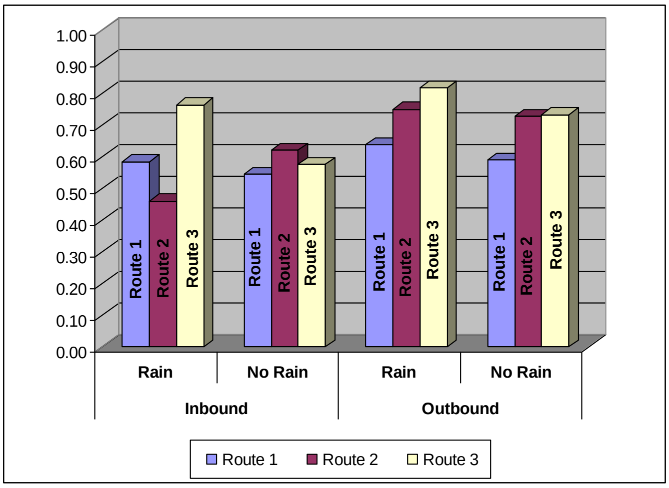

Fig. 2: Headway regularity index

D. Bus Bunching

Bunching is when busses come two or three at a time leaving a longer period of time than scheduled for the following bus to arrive. Bunching is a significant problem on many routes. The larger the headway irregularity index the more likely it is that bunching occurs. This section investigates whether adverse weather conditions have an impact on this performance measure.

Fig. 3 shows the results of the study with regard to bunching. The chart displays the times when a bus arrived at one particular bus stop on the horizontal axis. The vertical axis shows the various routes and weather conditions. Each square represents the arrival of the bus at the bus stop. The first observation is that bunching generally occurs whether it rains or not. No clear trend could be extracted from the bunching analysis. There might be a slight trend to less bunching on rainy days but it is not well defined. This would coincide with the findings from the headway regularity analysis.

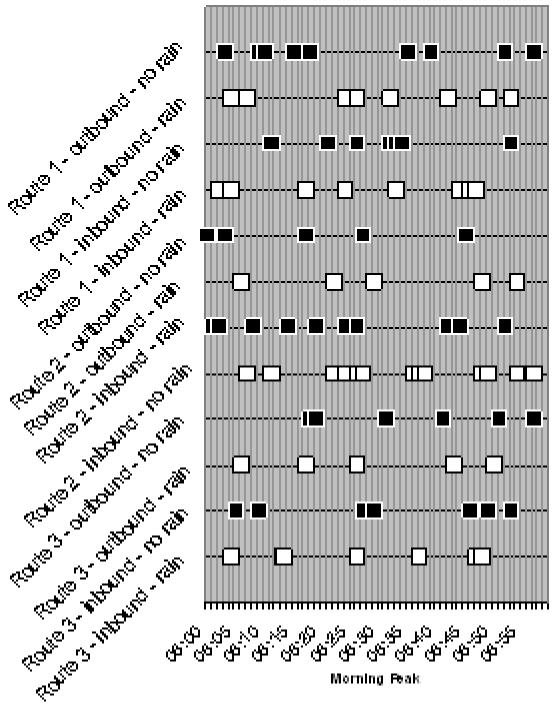

Fig. 3: The impact of adverse weather conditions on bunching

E. Travel Time

Travel time is the average duration of a trip from origin to destination [9]. For the purpose of this study, it was decided to extract the travel time of the entire route in minutes (i.e. time of last stop of the route minus time of the first stop of route). This performance measure is generally used to monitor services and to assess comfort levels. The average trip times of several test dates were extracted and analysed. The public, decision makers, transit managers and metropolitan planning organisations are generally interested in such measures.

The analysis of the impact of adverse weather conditions with regard to the travel time is very distinct. Table III and Fig. 4 show the detailed results from the travel time analysis. The analysis included three routes and 5 test dates where the total travel time of each route in minutes was extracted. Average trip travel times were 10 minutes (Route 4), 6.4 minutes (Route 5) and 10 minutes (Route 6) longer on rainy days than they were on non-rainy days. It can therefore be assumed that adverse weather has a negative impact on travel time.

TABLE III: TRAVEL TIME – MORNING PEAK

	Route 4		Route 5		Route 6	
	Rain	No Rain	Rain	No Rain	Rain	No Rain
Test Date 1	80	52	53	47	55	45
Test Date 2	75	57	58	51	56	40
Test Date 3	57	64	56	45	69	64
Test Date 4	77	70	53	50	64	53
Test Date 5	83	79	47	42	53	45
Average	74.4	64.4	53.4	47.0	59.4	49.4
St. Dev.	10.2	10.6	4.2	3.7	6.8	9.4

***** Grey areas show when the trip time was less on non-rainy days. Need to insert titles and units on top of the columns in this table

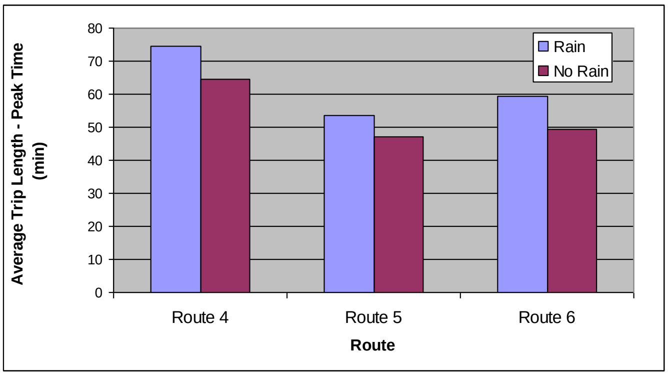

Fig. 4: Average trip length - peak time (in minutes)

F. *Travel Time Variability*

This performance measure is the variability of the average duration of a passenger trip. It is often used to measure comfort and to monitor service performance on a segment, route and system level. The general audience for such a measure is the public, decision makers, transit managers, schedulers, metropolitan planning organisations and transportation engineers. The travel time variability determines how often a passenger arrives at her/his destination by the expected time and also how much extra time the passenger must allow to reach their destination by a definite time. The standard deviation (SD) is sometimes used to analyse the variability of travel times. Smaller SDs can sometimes improve customer satisfaction [9]. The standard deviation of travel time on rainy and non-rainy days is very similar for routes 4 and 5. Route 6 on the other hand shows a greater difference. The travel time variability is greater by 2.6 minutes on non-rainy days. Routes 4 and 5 have the advantage of a dedicated bus corridor whereas route 6 connects urban areas on regular roads.

V. CONCLUSIONS

The following conclusions can be drawn:

- Electronic fare collection data can be combined with other databases such as weather data to produce urban bus performance measures and thus contribute to the general understanding of passenger behaviour.
- The ridership of magnetic strip card holders is lower on rainy days than on non-rainy days. This applies to morning peak, evening peak and off peak periods.
- A paired t-test provided statistical evidence that the mean frequencies of rainy days are not the same as for non-rainy days. The frequencies of inbound journeys are higher on non-rainy days. The average daily frequencies (inbound and outbound) are higher on non-rainy days. This may be due to the existing increase in traffic congestion.
- The headway regularity index showed that the service seems to be more regular when looking at headways on rainy days. This was true for all but one observation. The analysis showed a slight trend towards less bunching on rainy days which would coincide with the findings from the headway regularity analysis.
- The analysis of the impact of adverse weather conditions on travel time is very distinct. Average trip level what does 'level'mean here? times were 10 minutes (Route 4), 6.4 minutes (Route 5) and 10 minutes (Route 6) longer on rainy days than they are on non-rainy days. It can therefore be assumed that adverse weather has a negative impact on travel time.
- The standard deviation of travel time of rainy and non-rainy days is very similar for routes 4 and 5. Route 6, on the other hand, shows a greater difference. The travel time variability is greater by 2.6 minutes on non-rainy days.

It seems that rain contributes to a more regular service with a slight trend to less bunching. This may be due to the increased traffic congestion which prohibits the buses to move more freely. Need to mention weakness in the analysis due to the small sample of data taken.

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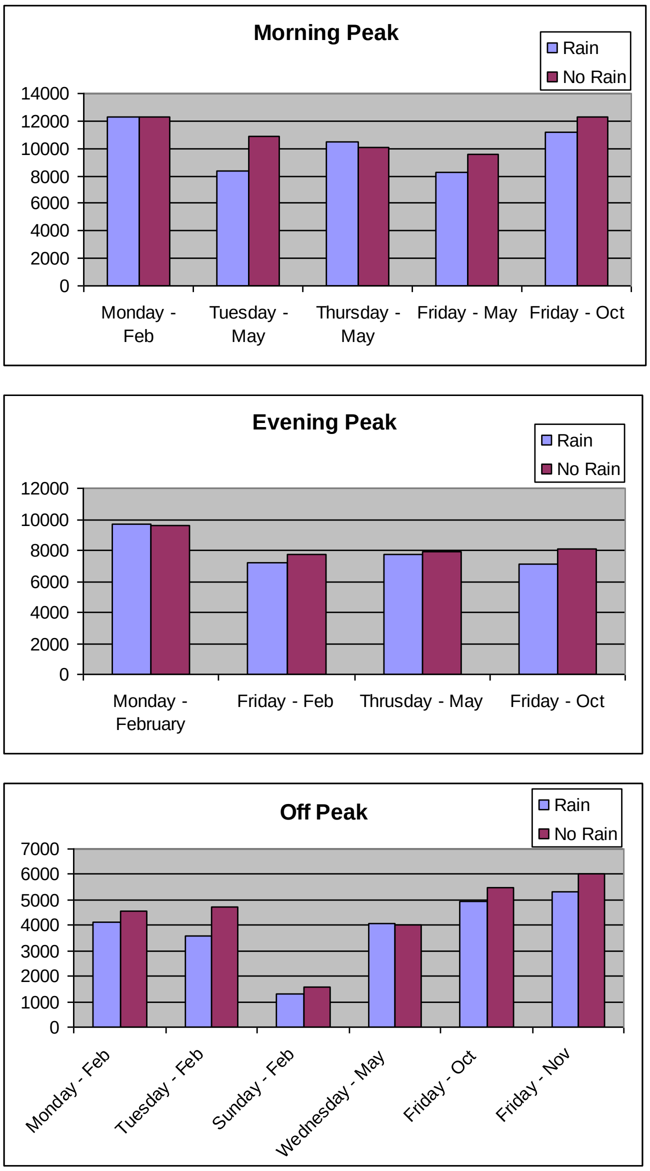

Fig. 1: Ridership of different peak/off-peak periods