Finding Comfortable Routes for Ambulance Transfers of Newborn Infants*

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Abstract— **Early inter-hospital ambulance transport of premature babies is associated with more severe brain injury. The mechanism is unclear, but they are exposed to excessive noise and vibration. Smart-routing may help minimise these exposure levels and potentially improve outcomes.**

An app for Android smartphones was developed to collect vibration, noise and location data during ambulance journeys. Four smartphones, with the app installed, were provided to the local neonatal transport group to attach to their incubator trolleys. An example of route comparison was performed on the roads used between Nottingham City Hospital (NCH) and Leicester Royal Infirmary (LRI).

Almost 1,700 journeys were recorded over the space of a year. 39 of these journeys travelled from NCH to LRI, comprising of 9 different routes. Analysis was performed on all recorded data which travelled along each road. For routes from NCH to LRI, the route with least vibration was also the quickest. Noise levels, however, were found to increase with vehicle speed. Ambulance drivers in the study did not tend to take the quickest, smoothest or quietest route.

Android smartphones are a practical method of gathering information about the in-ambulance environment. Routes were found to vary in vibration, noise and speed, suggesting these could be minimised. The next step is to combine recorded and clinical data to try and define an ideal neonatal comfort metric which can then be fed into the routing. Roll-out of the app around the UK is also planned.

Clinical relevance—**Transferring preterm neonatal infants to specialist units lead to worse outcomes. By reducing the levels of vibration and noise the infants are exposed to during transport, we hope to improve outcomes.**

I. INTRODUCTION

In the UK, high-risk sick and premature infants often require transferring by ambulance, due to centralisation of neonatal intensive care. Compared to non-transported premature infants, transported babies have more severe brain injury [1], [2], [3]. While the reasons for this are not fully understood, studies have shown that both vibration and noise are at excessive and potentially harmful levels inside ambulances [4], [5], [6], [7]. A reduction in these environmental stressors could improve outcomes.

Significantly reducing vibration and noise levels requires redevelopment of the ambulance and transportation equipment. In the meantime, the external inputs to the ambulance could be reduced by routing the ambulances along smoother or quieter roads.

To determine the most comfortable route options, details of how journeys along different roads compare must be known. Traditionally, gathering road condition information is expensive and therefore only performed annually [8]. Bespoke sensors were used for a previous study [6], however these were not suitable for large scale data collection. By utilizing the multitude of built-in sensors within ubiquitous smartphones, this can be achieved more cost-effectively.

This paper outlines how data from smartphone accelerometers and microphones, collected by neonatal ambulance services, could help reduce neonatal discomfort during transfers. Unlike most other smartphone-based studies, the aim here is to measure the effect on the vehicle environment – including noise levels – rather than features of the road itself.

II. ANDROID APPLICATION

A. Functionality

Long-term data collection is essential to ensure the large range of routes travelled are assessed and to capture road changes over time. As the app was to be used during clinical services, it was also imperative that patient care was not impeded. Therefore, operation of the app was via a single button for starting and stopping recordings, with large, clear buttons also used to input metadata about the ambulance journey.

No neonatal comfort index has been specified, however adult comfort can be derived from accelerations between 0.5 and 80 Hz [9]. According to the Nyquist-Shannon theorem, analysis of these frequencies would require sampling at a minimum of 160 Hz. Accelerations were sampled from the 3-axis accelerometer at the fastest rate possible, which varies between devices but is typically between 100 and 200 Hz.

Recording raw audio would compromise patient privacy, therefore, the maximum sound amplitude level was logged over 20 ms intervals. This was acquired by using a timer to call a built in method that was found to return false values of zero if called faster.

Location data is required to associate the recorded environment conditions with the road travelled over. All available data from the satellite receiver was logged at a rate of 1 Hz.

Time stamps assigned to noise and location data corresponded to the next accelerometer sample, as this had the highest sampling frequency. After each accelerometer sample all variables, along with the system timestamp, were written

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TABLE I

SAMPLE FREQUENCIES OF THE XIAOMI REDMI 5 PLUS.

Data Type	Sample Frequency (Hz)
Acceleration	200
Noise	50
Location	1

to comma separated strings which are then logged to a file periodically.

B. Validation

Four smartphones (Redmi 5 Plus, Xiaomi, Beijing, China) were used for data collection, fulfilling the accelerometer sampling requirement with a maximum frequency of 200 Hz (Table I).

The smartphones were found to match to within 10% of a reference accelerometer (352C65, PCB Piezotronics, Depew, NY, USA) up to 58 Hz subject to single-frequency sinusoidal excitation.

Noise levels from the microphones were found to match the maximum A-weighted values from a precision sound meter (2260 Investigator, Brüel & Kjær, Nærum, Denmark) up to 80 dB when subjected to pink noise.

Both accelerometer and noise values were similar at the same locations for multiple journeys. Comparing 35 journeys recorded along the same stretch of single carriageway resulted in an average inter-quartile range along the route of -0.09 - $+0.13$ $m{\cdot}s^{-2}$ and $\pm$ 1.4 dB in noise levels.

III. DATA COLLECTION

A. Method

The four smartphones were provided, pre-loaded with the app, to the local neonatal transport team to record all of their ambulance journeys.

Being a low-impact environment inside the ambulance, magnets were chosen to ensure secure mounting withstanding vertical shocks of up to 10g (Adhesive 10mm dia x 1mm N42 Black Epoxy Magnets - 0.58kg Pull, Magnet Expert Ltd, Tuxford, Notts., UK). These were arranged to permit only one correct alignment which ensured the smartphones were positioned consistently on the neonatal transport trolleys for every recording and therefore ensured all results were reproducible and comparable. The magnets were located at the rear-left corner of each transport trolley with the smartphone axes aligning with those of the ambulance (as shown in Fig. 1), ensuring reorienting of axes was not required and that driving style could be analysed alongside vertical vibration. The use of magnets was found to have a near-perfect transfer of vibration under sinusoidal testing.

Environmental information was supplemented by additional data about each journey to enable further analysis of possible causes and effects. At the start of each recording, the user inputted the ambulance and transport trolley IDs, and whether a patient is on board. On culmination of the recording, the use of any emergency driving is noted and, if a patient was transported, the reason for transfer.

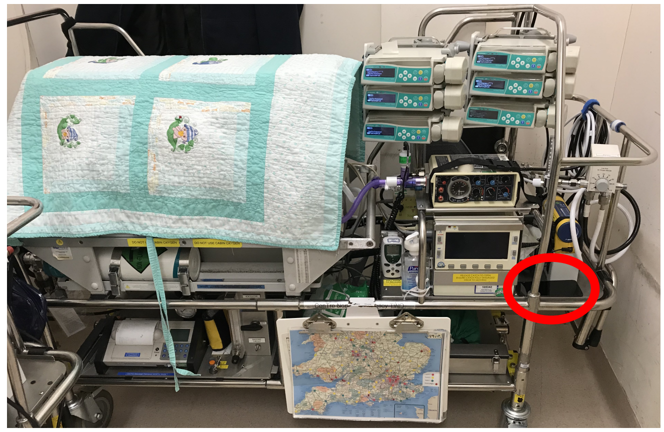

Fig. 1. Photo of one of the neonatal transport trolleys used during data collection with the smartphone attached (circled).

B. Outcomes

From 24/10/2018 until 14/10/2019, a total of 1,681 neonatal ambulance journeys undertaken by the CenTre Neonatal Transport teams were successfully recorded totalling a distance of over 95,000 km. Journeys were recorded in approximately equal proportions from each of the four ambulances and transport trolleys of the transport group, showing equal usage by all personnel. As an example of the additional clinical data collected, 45% of journeys involved patient transfers of which only 6% involved an element of emergency driving.

IV. PROCESSING

All recorded data were automatically retrieved and inserted into a time series relational database. Raw, unprocessed data were divided into two tables: one containing accelerometer and noise values; the other containing all location-related information. Metadata for each recording (phone used, start time and the clinical data as described above) were stored as index keys, both to facilitate comparisons and to minimise the risk of data being overwritten.

The standard for perceived adult comfort [9] was used as an initial indication of the neonatal risk to vibration as a neonatal comfort index has yet to be defined. Frequency weightings were applied to the raw accelerometer values for each data set, before being inserted into a third table in the database along with the total combined vibration values.

A network of all roads recorded was created to enable easy aggregation of all data which had travelled along a particular section. Unique segments are formed using plus codes (a form of incremental geocoding system in the form of single, short strings [10]) to split up routes based on junctions at which two or more journeys diverged.

Segments were assessed by grabbing data from each journey which travelled along it and averaging their total vibration values and median noise levels. These segment values were then combined proportionally with duration to produce final route values.

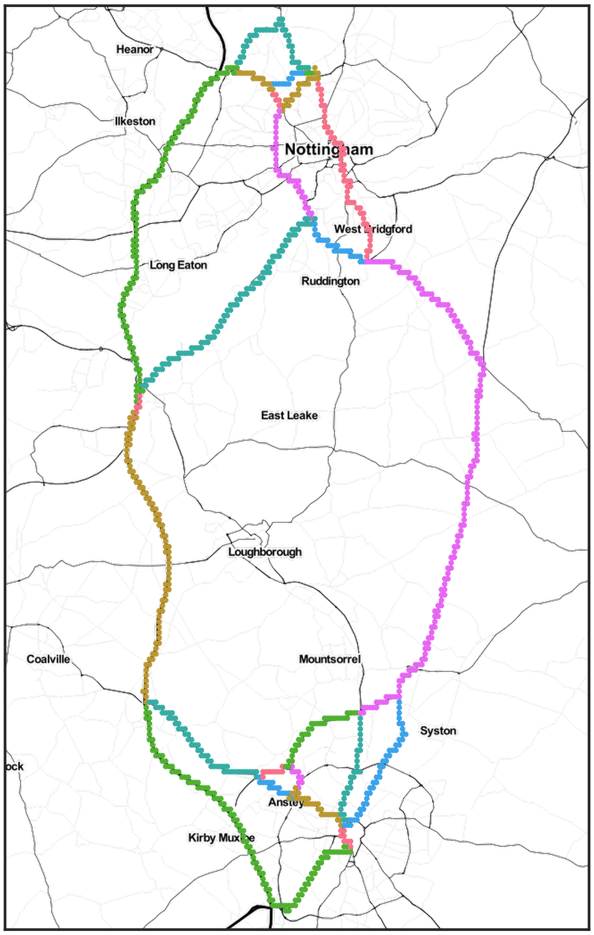

Fig. 2. Plot of unique sections of road between Nottingham City Hospital and Leicester Royal Infirmary. Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL.

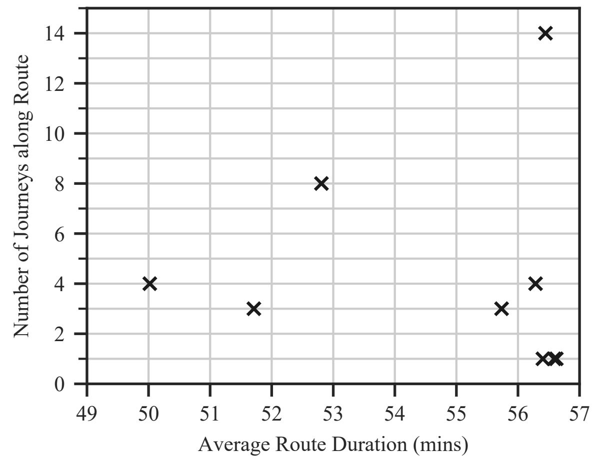

Fig. 3. Scatter plot showing the average duration for each route and the number of journeys from NCH to LRI which used it.

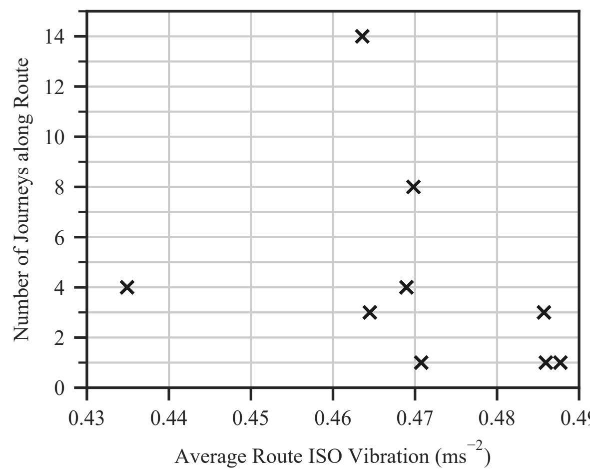

Fig. 4. Scatter plot showing the average ISO-weighted vibration for each route and the number of journeys from NCH to LRI which used it.

V. ROUTING

Road choices between the two bases of the neonatal transport group, Nottingham City Hospital (NCH) and Leicester Royal Infirmary (LRI), were analysed as an example of how recorded data may be utilised. Over the course of 12 months, 39 journeys travelled from NCH to LRI, taking 9 different combinations of roads. Performing network analysis on these journeys resulted in 25 edges (unique sections of road) which could be combined to form 16 different routes (Fig. 2).

Ambulances are provided with satellite navigation systems to help direct drivers from ’A’ to ’B’. Typically, this provides the fastest route, however drivers may diverge from the route using personal judgement based on experience and local knowledge. Having information about the effect of roads on the in-ambulance environment would provide drivers with a most comfortable route option, as well as advising on which roads should definitely be avoided.

The in-ambulance environment could be more reliably determined by including analysis from the rest of the 1,681 recorded journeys. Including these journeys resulted in a threefold increase in the average number of data sets per edge (51 vs 17) and a maximum of 206 datasets being aggregated for any one section.

Average durations for each of the 9 routes used between NCH and LRI, along with their usage, are shown in Fig. 3. Optimising the route to minimise vibration magnitudes resulted in a 10% decrease compared to the average of all routes (0.43 vs 0.47 ms^{-2}). In this case, this route was also the shortest in terms of time, saving 10.7% compared to the average for all routes (50.0 minutes vs 56.0 minutes).

Fig. 4 shows the number of times each route was used when travelling from NCH to LRI plotted against the average ISO-weighted vibration for that route.

Average 10 m audio levels varied minimally (69.1 dB - 71.7 dB) between the 16 possible route combinations, with a clear correlation (r^2=0.91) between average vehicle speed and noise.

Fig. 5 shows the number of times each route was used

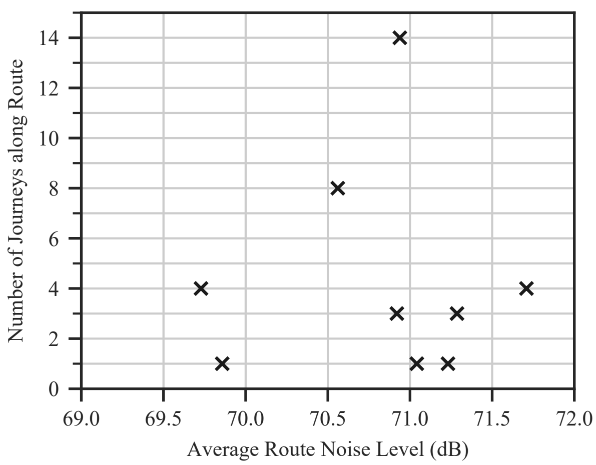

Fig. 5. Scatter plot showing the average noise level for each route and the number of journeys from NCH to LRI which used it.

when travelling from NCH to LRI plotted against the median noise level for that route.

VI. DISCUSSION / IMPACT

By using a smartphone app, the vibrations and noise levels inside ambulances have been recorded with a view to providing a most comfortable route to improve outcomes of neonatal hospital transfers. Data collection was embraced by the neonatal transport group with almost 1,700 journeys in 12 months recorded. Attaching to the neonatal trolley, along with more than 50 times the amount of data in any previous study [6], [7], [11], [12], allows a better understanding of what the baby is experiencing.

Roads driven from Nottingham City Hospital to Leicester Royal Infirmary were analysed to see the effect of route choice on potential comfort. Having such a large data set enabled analysis to be expanded from the 39 recordings directly between NCH and LRI, to an average of 51 journeys per unique section. By performing analysis on a larger set of data, confidence in the aggregated data was increased and trends became more evident.

In this case study, the route with the lowest average vibration magnitude also had the highest average vehicle speed and the lowest duration.

A limitation of the vibration optimisation was that it was based on adult focused metrics. However, without neonatal specific data, minimisation of total vibration is the best option available.

Although noise levels increase with vehicle speed for the routes investigated, there was little variation in the average route value. Unless the average noise level is found to significantly affect the comfort of a neonatal infant, it will have minimal impact on routing.

Depending on the metric, or combination of metrics, it is clear that the optimal route will be a compromise between the set of roads and the speed at which to travel.

The most common routes taken by the ambulance drivers in this study were not the quickest, smoothest or quietest. We have shown that a more informed route selection can reduce the levels of vibration and noise that neonatal infants are exposed to during transfers.

Whilst vibration and noise can be reduced, a neonatal comfort index is required to provide a true most comfortable route. By combining recorded vibration and noise data with clinical assessments performed after transfers, we may be able to identify elements of causality.

We will also be rolling-out the app to the rest of the neonatal transport groups in the UK. Crowdsourcing such data will lead to a greater amount of journeys recorded, covering a larger road network. We will then be able to analyse more routes with an aim of providing all groups with optimum routes for comfort and therefore improve the outcomes of all transferred infants.

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