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GIS-based framework to manage Whole-Body Vibration exposure

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ABSTRACT

A large number of workers are exposed to Whole-Body Vibration (WBV) on a daily basis. In the construction sector, the risk associated with vibration exposure is high as driving vehicles in areas with unpaved-roads or uneven surfaces is a very common activity. Drivers may be exposed to high levels of WBV, which may lead to the development of musculoskeletal disorders. Accordingly, this study developed a GIS-based methodological framework to reduce and manage WBV exposure in the process of routes design. The framework, providing the optimal route using a least-cost path analysis using the optimising criteria of travelled time and WBV exposure, was established. The methods set out in EU-Directive 2002/44/EC and ISO2631-5:2018 are applied. A case study was conducted in order to illustrate the proposed methodological framework. The information provided by the framework can be used by the construction companies and safety management to protect construction workers from excessive WBV exposure.

1. Introduction

Workers in different occupational sectors are exposed to physical hazards in the workplace such as noise and whole body vibration (WBV), with the construction sector being one of the most prevalent [1]. Noise exposure has determined the need to develop management models, both to protect the health of workers and to ensure the acoustic comfort to dwellers near the construction sites [2–5]. In the case of vibration exposure, construction workers might also be exposed to WBV on a daily basis by driving delivery vehicles or heavy equipment vehicles (such as earth moving equipment, trucks, dumpers, etc.) [6,7]. In fact, many of the activities carried out with such vehicles are performed on uneven surfaces, which imply a higher level of exposure to WBV, and mechanical shocks compared to activities performed on regular surfaces [8,9]. It should be noted that vehicle operation is not limited to the construction site; the transport of construction materials accounts for up to 30% of traffic in cities and represents up to 30% of the tonnage transported in cities [10]. In general, the perception of comfort during vehicle driving is closely related to WBV, with the pavement performance being a critical factor in the driving comfort experience and drastically affecting the safety management of roads [11].

This situation is a major cause of concern within the workforce because this condition is associated with the development of a number of adverse health conditions, including the potential development of various neuropathies [12], digestive problems [13,14] and possibly cancer [6,15]. Moreover, previous research has shown epidemiologic evidence that relates this physical exposure at work to the development of work-related musculoskeletal disorders (WMSDs) [16,17], which have a high impact on health and reduce the quality of life of workers during their working life and retirement. These health problems include degenerative changes in the lumbar spine [5,18–21], low back pain [22–24], sciatica [25], neck pain [9,26,27] and disorders such as motor performance [28].

Currently, about a third of the worldwide population [29] and more than half of European workers face WMSDs [16]. Construction workers are among the workers with the highest prevalence of this type of disorder [1,30]. The research conducted by Wahlström J. et al. [19] showed that there was an increased risk for hospitalisation due to lumbar disc herniation for workers in the construction industry exposed to medium to high WBV compared to white-collar workers and foremen. Although in literature numerous studies have addressed construction safety problems from different facets [31,32] and some of them focused on the equipment and vehicles use in construction sector [33–36], less or little attention has been paid to the problems related to vibrations and driving delivery vehicles (e.g. concrete mixer truck).

These circumstances mean that WMSDs are a significant global health problem with important socio-economic consequences, with a great impact on the most affected sectors. In consequence, governments

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have sought strategies for the minimisation of the risks from WMSDs. In this context, the EU published the Directive 2002/44/EC [37] with the aim of laying down minimum requirements for the protection of workers from risks to their health and safety arising from, or likely to arise from, exposure to mechanical vibration. This directive is complementary to the European Framework Directive on Safety and Health at Work [38] adopted in 1989.

Directive 2002/44/EC establishes that the WBV exposure assessment methods are those defined in ISO 2631-1:1997 [39], the daily exposure A(8) and the vibration dose value (VDV). In addition, it defines daily exposure limit values for vibrations, the Exposure Action Value (EAV) and the Exposure Limits Value (ELV). However, both methods provide the assessment of daily exposure to WBV without considering the cumulative exposure to vibrations over longer times. In this context, ISO 2631-5:2018 [40] has recently been published. This standard defines two exposure regimes to assess the risk of chronic injury from exposure to repeated shock based on the predicted biomechanical response of the bony vertebral endplate (hard tissue). It also provides values to determine whether the probability of an adverse health effect due to prolonged exposure to WBV is low, moderate, or high.

This regulatory framework has been defined mainly with a preventative character. In this sense, vehicle transport routing techniques can be included as a Prevention through Design (PtD) Tool [41] in order to manage the exposure of drivers to WBV.

Furthermore, routing techniques for the identification of the most suitable path have been significantly enhanced by Geographic Information Systems (GIS) and the development of the application of spatial optimisation techniques. The Dijkstra's algorithm [42] is one of the most widely used techniques for optimal routing analysis in GIS. This algorithm provides the Least-Cost Path (LCP) between two nodes in a network based abstraction. Several studies have shown that this LCP analysis can be used to optimise transport routes: Marc Schröder and Pedro Cabral [43] propose a model based on a 3D-road network for the minimisation of fuel consumption and CO_2-Emissions; Sosa et al. [44] used a network-based spatial analysis to estimate the least-cost route for the distribution of biomass with the use of GIS; Abdul Hakim Salleh et al. [45] and Bueno-Delgado et al. [46] proposed a route optimisation method as a solution to the problem of waste collection using network analysis. However, a vector-based network data structure that only includes road data cannot be applied in areas without roads, or with temporary unpaved roads.

Off-road driving is a very common activity in the engineering and construction sector since the execution of projects may require travel in areas without roads. Aiming to solve this problem, many studies use a raster-based least-cost path algorithm based on Dijkstra's algorithm. This technique is broadly used in real-world applications such as finding layout planning in large earthmoving projects [47], minimising environmental impacts of power lines [48] and optimising earthmoving job planning [49]. However, the LCP analysis has not been implemented for the purpose of managing WBV exposure in transport operations.

In this context, this research develops a GIS-based methodological framework to identify the *optimal route* using an LCP analysis to manage WBV exposure. The proposed framework aims to offer a novel approach which provides easy visualisation of the routes and reliable information to support decision-making in the field of safety management. For this purpose, the *optimising criteria* of travelled time and WBV exposure are established. In this framework, the assessment method established in Directive 2002/44/EC is implemented in order to determine the probability of suffering health problems due to WBV exposure. The route obtained is displayed in the GIS software and the WBV exposure data is registered. From these results, a data base can be created to monitor and manage the worker's WBV exposure over time. Finally, an illustrative case of application of the proposed methodology is shown.

The structure of the paper is given as follows. Section 2 provides the preliminary concepts and the spatial analysis techniques applied in this study. This section gives detailed information about the WBV assessment methodology and the LCP analysis. Section 3 describes the proposed methodology and the criterion for the route design optimisation. Section 4 illustrates the proposed methodology with a case where the methodology is applied. Finally, Section 5 provides discussion, and Section 6 provides final judgements and conclusions.

2. Preliminary concepts and spatial analysis techniques

2.1. Whole-body vibration assessment

As stated in the introduction, the methods for assessing the risk associated with WBV exposure are defined in both ISO 2631-1 and ISO 2631-5. Both methods use the acceleration recorded and measured on the seat surface in representative situations. This data is used to estimate the WBV exposure dose, which is extrapolated from this measurement to a recorded exposure duration in the past, or to a predicted exposure duration in the future. The following sections summarise the procedure used in both standards.

2.1.1. ISO 2631-1:2008 parameters

This standard defines two methods, the daily exposure A(8) and the vibration dose value (VDV), which are both referred to in the EU directive (Directive 2002/44/EC) for the assessment of exposure to WBV in the workplace. Both methods are based on the calculation of the root mean square (rms_w) of the weighted averaged acceleration and the vibration dose value (vdv_w), respectively.

According to the ISO 2631-1 standard, Butterworth filters are used to weight the acceleration in frequency for calculating the first parameter. The z-axis is weighted using weight denoted as W_k and the x- and y-axes using W_d. The root mean square (rms_w) of the weighted averaged acceleration (m/s^2) is then calculated as the second power of the acceleration time history as the basis for the averaging process (Eq. 1):

$$rms_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{1}$$

where *aw* is the frequency-weighted instantaneous acceleration (W_d on x and y axes, W_k on z axis), and T is the time duration of the measurement.

The vibration dose value (vdv_w) is calculated as the fourth power of the acceleration time history (Eq. 2), so this parameter is more sensitive to peaks than the rms_w:

$$vdv_w = \left[\int_0^T a_w^4(t)dt\right]^{\frac{1}{4}} \tag{2}$$

In order to determine the worker exposure assessment according to Directive 2002/44/EC, the daily exposure value ($A(8)$) (Eq. 3) and the vibration dose value method (VDV) for each axis (Eq. 4) are then calculated as follows:

$$A(8)_i = k_i \, rms_{iw}\sqrt{\frac{T_{exp}}{T_0}} \tag{3}$$

$$VDV_i = k_i \, vdv_{iw}\sqrt[4]{\frac{T_{exp}}{T_{meas}}} \tag{4}$$

where i denotes the x, y, and z-axes, k denotes the multiplication factor defined for each axis ($k_{x,\,y} = 1.4$ and $k_z = 1$), T_{meas} is the measurement period, T_0 is the reference duration of eight hours, and T_{exp} is the daily duration of exposure to the vibrations.

In those cases where the subject is expose to WBV in two or more operations with different vibration magnitudes, the partial vibration exposure values are combined to obtain the overall daily exposure value. In this case, the value of the parameters A(8) (Eq. 5) and VDV (Eq. 6) can be calculated as:

$$A(8)_i = \sqrt{\sum_j^n A(8)_{ij}^{\;2}} \tag{5}$$

$$VDV_i = \sqrt[4]{\sum_j^n VDV_{ij}^{\;4}} \tag{6}$$

where *i* denotes the x, y, and z-axes, j denotes the *j*-th WBV exposure, *n* is the total number of WBV exposure operations, $A(8)_{ij}$ is the $A(8)$ value for the i-th axis in the j-th operation, and VDV_{ij} is the VDV value for the i-th axis in the j-th operation.

Subsequently, the highest of the three single axis values can then be compared with the Daily Exposure Action Value ($A(8) = 0.50\ m/s^2$ and $VDV = 9.10\ m/s^{1.75}$) and the Daily Exposure Limit Value ($A(8) = 1.15\ m/s^2$ and $VDV = 21.00\ m/s^{1.75}$) established by the EU directive (Directive 2002/44/EC).

2.1.2. ISO 2631-5:2018 parameters

This standard defines two assessment methods based on different exposure regime conditions. This research implements the method that addresses what the standard calls "less severe conditions", as the activities considered do not contain exposure to WBV with free-fall events and the subject does not lose contact with the seat surface due to the shock.

This method requires as input the acceleration time series. The measurement data from the seat surface can also be used as input for the backrest surface if this data is not available. In addition, the model also needs as input the exposure time periods (hours per day, and days per year), the life-time exposure history, the Posture Group, and the anthropometric characteristics of the drivers (body mass and height). In cases where the life-time exposure history data are not available, or in order to compare different exposures, the Appendix A of the standard states that the analysis should be accomplished assuming the most unfavourable exposure conditions. The values of the exposure time periods (hours per day, and days per year) and the life-time exposure history are chosen in such a way that they maximise the spinal load.

On the basis of this data, the intervertebral compressive forces, and the maximum daily compressive dose for the six disc levels of the lumbar spine (T12/L1, L1/L2, L2/L3, L3/L4, L4/L5 and L5/S1) were calculated as follows (Eq. 7):

$$S^A = \left(\sum_i \left(\frac{c_{dyn,i}}{B}\right)^6\right)^{\frac{1}{6}} \tag{7}$$

where $c_{dyn,\ i}$ (N) stands for the sum of peak compressive forces acting on the vertebral endplate, and B (mm^2) is the area of the vertebral endplate. The equivalent daily compressive dose (S_d^A) is calculated considering the total duration of the exposure during a day (Eq. 8):

$$S_d^A = \left(\sum_j^n S_j^{A6}\ \frac{t_{dj}}{t_{mj}}\right)^{\frac{1}{6}} \tag{8}$$

where S_j^A is the dynamic compressive stress of the lumbar spine due to vibration exposure to operation *j*, t_{dj} is the time period of the daily vibration exposure to operation *j*, t_{mj} is the time period over which S_j^A has been measured, j is the *j* -th operation which exposes the worker to WBV, and *n* is the total number of operations which expose the worker to WBV.

The Risk Factor R^A for every disc level is estimated based on the S_d^A:

$$R^A = \left(\sum_{m=1}^{n}\left(\frac{S_d^A\ N_m^{\frac{1}{6}}}{S_{u,m}^A - S_{stat,m}^A}\right)^6\right)^{\frac{1}{6}} \tag{9}$$

$$S_{u,m}^A = 6.765024\ MPa - 0.067184\ MPA\ (b+m) \tag{10}$$

where *m* is the year counter, N_m is the number of exposure days per year *m*, *n* is the number of exposure years, $S_{u,\ m}{}^A$ is the ultimate strength of the lumbar vertebra for a person of age *(b + m)* years with *b* being the age at which the exposure started, and $S_{stat,\ m}{}^A$ is the mean value of the compressive-decompressive force divided by the area of a vertebra endplate B (mm^2) for year *m*.

2.1.3. Health guidance caution zone (HGCZ)

The exposure assessment methods for WBV exposure specified in ISO 2631-1 are adopted in the European Directive 2002/44/EC. This EU directive also determines standardised limits to an 8-h exposure reference period. In addition, boundaries for the emergence of probable health effects derived from multiple shocks vibration exposure are defined in ISO 2631-5:2018 (Table 1).

2.2. GIS least-cost path algorithm

The LCP analysis is a technique of finding a sequence of cells between an origin cell and a destination cell with the least possible cost in a raster space [50]. This technique finds least-cost paths by considering a hypothetical network on a raster. In this hypothetical network, one node is considered for each cell center, and each node is connected to its adjacent nodes by multiple links [51].

In this context, GIS technologies have proven to be quite valuable in the process of implementing such techniques. This analysis is based on applying algorithms such as Dijkstra's *shortest path* algorithm [42] and the back-link mechanism of Xu and Lathrop [52] on a cost raster. Dijkstra's algorithm allows creating a path on a cumulative cost surface. This algorithm is executed as a sequence of steps: in the first step, the shortest weighted distance (or accumulated travel cost) is calculated for each raster cell to the give origin cell over a cost surface. This process differs from the Euclidean distance, which is a simple function of a straight line between two points [53]. The cost distance tool utilises the node/link cell representation used in graph theory. Each link that connect the cells has an impedance with it. The impedance value is derived from the costs associated with the cells at each end of the link (from the cost surface dataset) and the direction of movement through the cells. The cost assigned to each cell represents the cost per unit distance to move through the cell. As a result, this tool returns as output, a raster in which each cell is assigned the accumulated cost up to the origin cell.

In the second step, the algorithm uses the path distance tool in order to find the least-cost path between the origin cell and the destination cell. This is a cost distance analysis tool accounting for the surface distance as well as the horizontal and vertical cost factors criteria.

3. Framework to manage whole-body vibration exposure

This study presents a GIS-based methodology to optimise WBV exposure in the process of routes design. The routing design process is optimised by minimising WBV exposure and minimising travel time. The model allows visualising the route that optimises both objectives and

Table 1
Health guidance caution zone.

Directive 2002/44/EC			ISO 2631-5:2018		
Exposure limit values and action values			Probability of an adverse health effect		
Exposure Action Value (EAV)	$A(8) =$ $0.50\ \frac{m}{s^2}$	$VDV =$ $9.1\ \frac{m}{s^{1.75}}$	Low	$S_d{}^A <$ $0.5\ MPa$	$R^A <$ 0.8
Exposure Limits Value (ELV)	$A(8) =$ $1.15\ \frac{m}{s^2}$	$VDV =$ $21.0\ \frac{m}{s^{1.75}}$	Moderate	$S_d{}^A >$ $0.5\ MPa$ $S_d{}^A <$ $0.8\ MPa$	$R^A >$ 0.8 $R^A <$ 1.2
			High	$S_d{}^A >$ $0.8\ MPa$	$R^A >$ 1.2

calculating the exposure associated with the obtained route. The methodology integrates the WBV assessment and the LCP model to obtain the optimum route according to the defined criteria. A general methodology overview is given in Fig. 1, where the connection between the data obtained from the field measurement and the consecutive phases of the methodology implemented in the ArcGIS software [54] can be seen.

The implementation of the methodological framework is divided into three stages: (1) Activity characterisation. In this first stage, field work is carried out, where the characteristics of the activity are analysed, and the acceleration transmitted through the seat and the time and position of the vehicle are measured. (2) Raster Map Calculation and routing process optimisation. In this second phase, the *optimal route* connecting a point of origin and a point of destination is calculated from the data obtained in phase 1. This process is carried out using the cost-distance tool in GIS. For this purpose, the ArcGIS software ArcMap [54] was used to implement the Spatial Analysis tools to measure the cost distance. (3) Visualisation and decision-making. Finally, the route obtained in the previous stage and the parameters associated with it (level of WBV exposure, time and distance travelled) are shown in this stage.

The methodological framework can also be applied to other optimisation criteria, as it provides the level of WBV exposure, and the time and distance travelled of the resulting route. This information can be used by the safety manager to support decision-making in the field of logistics and supply chain management, as well as worker health and safety management.

3.1. Stage 1: Activity characterisation

Since WBV exposure depends on different factors [55], the characteristics of the activities that the driver performs with the vehicle must be analysed. In this sense, the following data must be collected: the characteristics of the activity (velocity, surface, and performance characteristics), driver characteristics (weight, height, age, and posture) and WBV exposure characteristics (exposure duration and if the exposure contains multiple shocks). This data is used as input for the defined

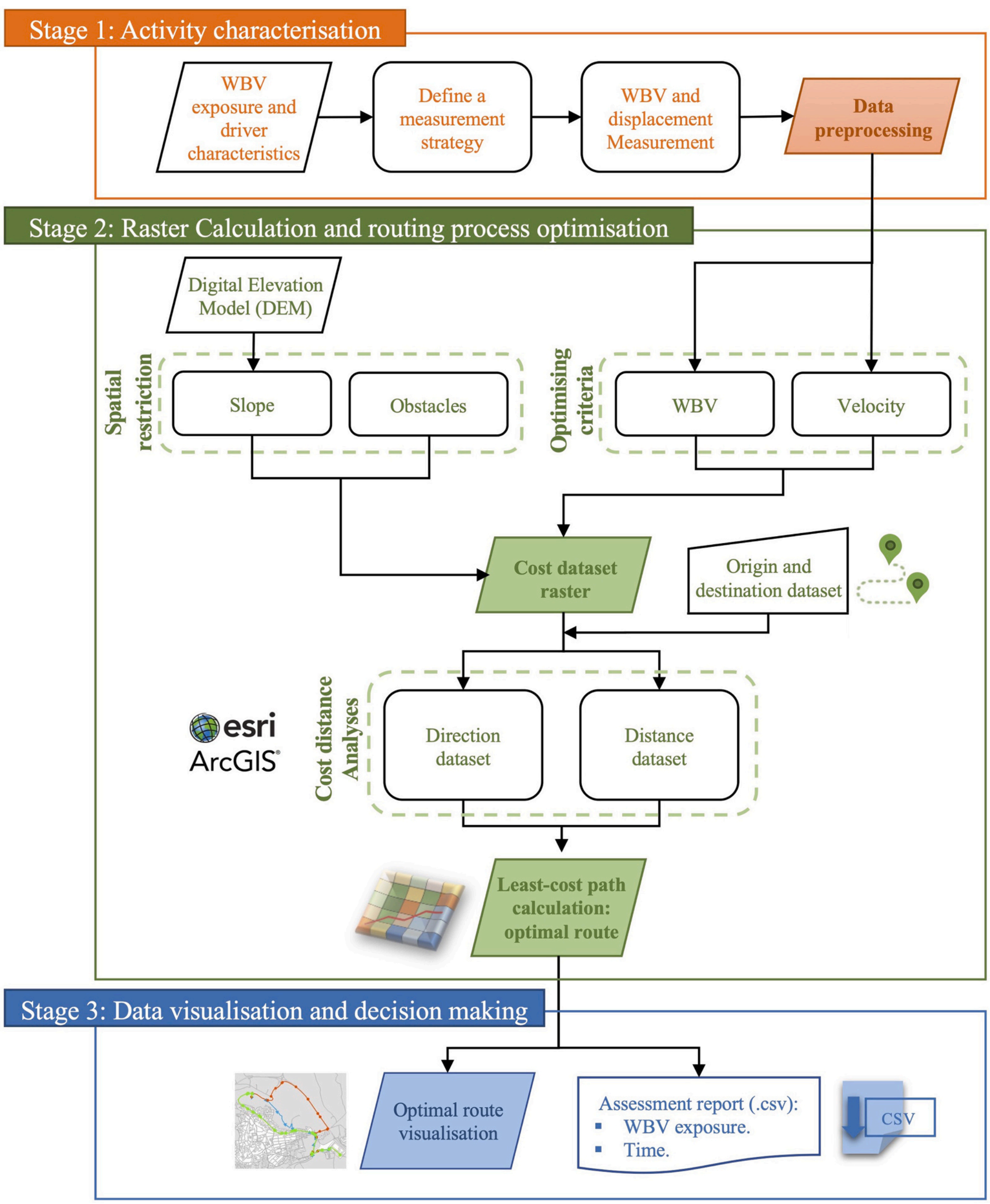

Fig. 1. Framework of the developed methodology.

methodology. The analysis of this data is used to define a measurement strategy which ensures that the data obtained are representative of the different exposure conditions as laid down in ISO2631-1 and ISO2631-5.

Once the measurement strategy is established, the speed of the vehicle and the acceleration at the interface between the driver and the seat of the vehicle must be measured. During data collection, the acceleration must be measured using a triaxial accelerometer disc placed on the seat pad. In addition, the time and position of the vehicle must be recorded simultaneously with a GPS logger. Both sensors must start the measurement simultaneously. In addition, since accelerations measured during loss of contact between the driver and the seat surface shall not be counted as exposure, the subject must remain seated without losing contact with the seat surface.

The data obtained from the measurement are subsequently used as input for the defined methodology. From these, the WBV exposure associated with each type of activity performed by the worker is estimated, considering the speed of travel of the vehicle and the nature of the surface where the activity is performed. The parameters A(8), VDV, and S^A must be estimated, as described in Section 2.

In addition, the average velocity ($\overline{v_s}$) of each different exposure condition must be estimated. On the basis of $\overline{v_s}$, it is possible to calculate the time taken to travel 1 km on each type of surface ($t_{1km,\ s}$). This parameter will be used to estimate the A(8), VDV, and S^A exposure values associated with travelling 1 km on each type of surface ($A(8)_{i\ 1km,\ s}$, $VDV_{i\ 1km,\ s}$, $S_{1km,\ s}{}^A$).

Since the exposure dose is a combination of the exposure quantity and the duration, the data obtained in the characterisation stage are used as input for the estimation of the daily exposure dose value. The exposure values normalised to $t_{1km,\ s}$ exposure duration are used to estimate the partial WBV exposure values associated with each type of exposure received by the worker in a day. Subsequently, these partial vibration exposure values are combined to obtain the overall daily exposure value as established in the Standards (section 2.1).

This characterisation stage makes it possible to generate a database with the different conditions of driver's activities and the associated WBV exposures values, key data for proper preventative risk management. This makes it possible to quantify the dose of WBV that each worker will be exposed to over the course of his or her lifetime at the workplace. The exposure measured in representative situations and the dose normalised to $t_{1km,\ s}$ is extrapolated to an exposure duration in the past or/and an anticipated exposure duration in the future:

$$t_{1km,s} = \frac{1}{\overline{v_s}} \tag{11}$$

$$A(8)_{i\ 1km,s} = \sqrt{\left(k_i\ rms_{ws}\ \sqrt{\frac{t_{1km,s}}{T_0}}\right)^2} \tag{12}$$

$$VDV_{i\ 1km,s} = \sqrt[4]{\left(k_i\ vdv_{iws}\ \sqrt[4]{\frac{t_{1km,s}}{t_{m,s}}}\right)^4} \tag{13}$$

$$S^A_{1km,s} = \sqrt[6]{S_s^{A6}\ \frac{t_{1km,s}}{t_{m,s}}} \tag{14}$$

where:

$t_{1km,\ s}$ is the time taken to travel 1 km on the s-th surface,

$\overline{v_s}$ is the mean velocity [km/s] to travel 1 km over the s-th surface,

$A(8)_{i\ 1km,\ s}$ is the exposure value A(8) in the i axis due to vibration exposure associated with travelling 1 km on the s-th surface,

i denotes x, y, and z-axes,

k_i denotes the multiplication factor defined for each i axis ($k_{x,\ y} = 1.4$ and $k_z = 1$),

rms_{iws} is the root mean square of the weighted averaged acceleration [m/s^2] in the i axis due to vibration exposure on the s-th surface,

T_0 is the reference duration of eight hours [s],

$VDVk_{i1km,\ s}$ is the Vibration Dose Value in the i axis due to vibration exposure associated with travelling 1 km on the s-th surface,

vdv_{iws} is the vibration dose value calculated as the fourth power of the acceleration time history [m/s^4] in the i axis due to vibration exposure on the s-th surface,

$t_{m,\ s}$ is the measurement time [s] on the s-th surface,

$S_{1km,\ s}{}^A$ the dynamic compressive stress of the lumbar spine due to vibration exposure [MPa] associated with travelling 1 km on the s-th surface,

$S_s{}^{A6}$ is the is the dynamic compressive stress of the lumbar spine due to vibration exposure [MPa] on the s-th surface.

3.2. Stage 2: Raster map calculation and routing process optimisation

Firstly, the *cost dataset raster* must be calculated. This process is based on two types of data: (1) a set of geospatial data (vector graphics such as polygons, lines, points, etc.) of the area under analysis; and (2) the data obtained in Stage 1 that will be used in the process of defining the optimisation criteria.

Regarding geospatial data, the road network of the area under analysis is required, as well as a Digital Elevation Model (DEM) raster and the location of obstacles and restricted vehicle access areas (*spatial restriction*). Currently, there are Open Data repositories that provide geospatial information from all over the world [56].

In the proposed methodology, two *optimising criteria* have been selected for the route design optimisation process (see Table 2). The first is to minimise the travelled time, for which the attribute t_{1km} must be created. In this attribute, the time taken by the vehicle to travel 1 km will be assigned to each type of surface. This parameter has been selected due to the impact it has on both the productivity of the company and the client. The second criterion is to minimise the WBV exposure of the driver. For this second criterion, the method laid down in ISO2631-1 has been selected and parameter A(8) has been applied. This parameter has been selected because the EU Directive 2002/44/EC states that A(8) is one of the methods on which the assessment of the level of exposure to vibration must be based. For this purpose, the attribute $A(8)_{1km}$ must be created. This parameter assigns to each type of surface the value of the daily exposure A(8) expressed as equivalent continuous acceleration over an eight-hour period associated with the displacement of 1 km.

Once the *optimising criteria* have been defined, the geospatial data must be pre-processed to add an attribute for each criteria in Table 2. Therefore, the attributes t_{1km} y $A(8)_{1km}$ must be created. These attributes are used to convert vector spatial data into raster data so that two raster maps are generated, one for each optimising factor's criteria. Both resulting rasters must be combined to provide a cost surface map. For this purpose, both rasters must be multiplied up on a cell-by-cell basis.

$$c = t_{1km,s} \bullet A(8)_{1km} \tag{14}$$

Additionally, *spatial restrictions* must be applied. This process aims to exclude areas that are not suitable for vehicle routes from the analysis. In this sense, spatial constraints must be applied to avoid routing in areas with obstacles, restricted vehicle access, and water bodies and buildings. In addition, areas with steep slopes (greater than 15%) can negatively affect travel performance and may not be safe for vehicle movement. The spatial analysis tools allow the analysis of the three-dimensional properties of landscape based on a DEM raster. Therefore, the use of this tool allows the calculation of the ground slope from a DEM and the identification of areas with a slope value higher than 15%. In order to exclude the areas that are unsuitable to hosting a route from the analysis, a high resistance cost value (such as 10000) is assigned to exclude it from potential routes. As a result of the process of combining both criteria raster maps and the subsequent application of *spatial restrictions*, the *cost dataset raster* is obtained.

Henceforth, the next step is the identification of the origin and destination dataset. These three elements are used as input for the *cost distance analysis* in ArcMap. The direction dataset and distance dataset

Table 2
Optimising criteria.

Criteria	Parameter	Unit	Equation	Description
Time	$t_{1km,\ s}$	[s]	11	Time taken to travel 1 km on the s-th surface;
WBV exposure	$A(8)_{1km}$	[m/s^2]	12	Highest A(8) value of the three directions (x,y,z) associated with travelling 1 km on the s-th surface.

obtained from this analysis are used as input to perform the cost path analysis. As a result, the route which provided the lowest-cumulative cost over the cost surface is obtained (Least-cost path calculation: *optimal route*).

This same procedure, detailed in Stage 2, can be repeated in order to obtain routes that set other optimisation criteria, such as the optimisation criterion of distance (i.e., shortest route) or travelled time (i.e., fastest route). The visualisation of the results in the same GIS software interface provides an easy overview of the routes and the WBV exposure results obtained.

3.3. Stage 3: Data visualisation and decision making

After executing the routing optimisation process, the resulting route will be displayed in the same ArcMap software interface. From this output, the distance travelled by the route on each type of surface is estimated. Based on this data, the time spent on the route is calculated in this stage of the methodological framework. The following equations are used:

$$t_{d,s} = l_{d,s}\ \frac{1}{\overline{v_s}} \tag{15}$$

$$t_r = \sum\nolimits_{j=1}^{p} t_{d,j} \tag{16}$$

where:

$t_{d,\ s}$ is the exposure time [s] on the s-th type of surface,

$l_{d,\ s}$ is the total distance [km] of the route over the s-th type of surface,

$\overline{v_s}$ is the average speed [km/s] of travel over the s-th type of surface,

t_r is the total time [s] taken by the vehicle to perform the route *r*,

j is the counter of the types of surface in the route *r*,

p is the total number of type of surfaces in the route *r*.

The $A(8)_{ir}$, VDV_{ir} and S_r^A values due to vibration exposure in the route is calculated using the following equations:

$$A(8)_{ir} = \sqrt{\sum_{s=1}^{p}\left(k_i\ rms_{iws}\sqrt{\frac{t_{d,s}}{T_0}}\right)^2} \tag{17}$$

$$VDV_{ir} = \sqrt[4]{\sum_{s=1}^{p}\left(k_i\ vdv_{iws}\sqrt{\frac{t_{d,s}}{t_{m,s}}}\right)^4} \tag{18}$$

$$S_r^A = \sqrt[6]{\sum\nolimits_{s=1}^{p} S_{1km,s}^{A6}\ \frac{t_{d,s}}{t_{1km,s}}} \tag{19}$$

where:

$A(8)_{ir}$ is the daily exposure value in i-axis in the route *r*,

VDV_{ir} is the vibration dose value in the *i*-axis in the route *r*.

S_r^A is the dynamic compressive stress of the lumbar spine due to vibration exposure in the route *r*,

In those cases where the driver only drives that route during the working day, the S_r^A, $A(8)_{ir}$ and VDV_{ir} values are equal to S_d^A, $A(8)_i$ and VDV_i values, respectively. In the case that the driver performs more than one route, the S_d^A, $A(8)_i$ and VDV_r values are calculated using the following equations:

$$S_d^A = \sqrt[6]{\sum\nolimits_{r=1}^{t} S_r^{A6}} \tag{20}$$

$$A(8)_i = \sqrt{\sum_{r}^{t} A(8)_{ir}^{\ 2}} \tag{21}$$

$$VDV_i = \sqrt[4]{\sum_{r}^{t} VDV_{ir}^{\ 4}} \tag{22}$$

where:

r is the *r*-th route,

t is the total number of routes driven during the working day.

The WBV exposure data is exported as a .csv file. From the results obtained, the safety manager can assess whether the exposure obtained is safe for the driver and whether preventative measures should be implemented in the short term (e.g., organisational measures, improvements in machinery, etc.). This process can be done by comparing the S_d^A, A(8) and VDV values obtained with the health guidance caution values (see Table 1).

In addition, the route optimisation process provides information to generate a lifetime exposure history profile. This data allows the calculation of the R_A parameter (see eq. 9) to assess the effect of cumulative WBV exposure on worker health (see Table 1). This analysis contributes to monitoring the worker's WBV exposure and to assessing whether he/she will suffer adverse health effects from long-term WBV exposure, in order to take preventative action to minimise them.

4. Case study

In order to illustrate the proposed GIS-based methodological framework, the application of it to a case study is shown below. The study was applied to a Concrete Plant site in Porcuna (Jaén). The activity analysed is the ready mixed concrete (RMC) delivery. In this activity, the RMC is manufactured at the batching plant to produce mix design strengths based on the client requirements [57]. The concrete is poured into mixer trucks for site delivery [58]. The study was applied to a Concrete Plan site in Porcuna (Jaén). This activity was selected because it is one of the most common in engineering and construction projects. This activity requires a high frequency of journeys to transport RMC to construction-sites. The number of journeys will depend on the total volume of RMC ordered by the client.

In the case study, the *optimal route* (based on the *optimising criteria* shown in Table 2), the fastest route (optimisation criterion of travelled time), and the shortest route (optimisation criterion of distance) were calculated. The proposed methodological framework automatically calculates, for each route, the parameters used in the *optimising criteria*: daily exposure A(8), the total distance travelled, and the total time taken to travel the route. Since there is no WBV exposure during operations at the concrete batching plant and the dispatching RMC in the construction site, theses parameters are only calculated during transit for site delivery.

4.1. Stage 1: Activity characterisation

With regard to the activity, the RCM delivery requires the driving of concrete mixer trucks on different types of surfaces. In addition, since some construction projects are built in sites far away from urban areas, RMC delivery may require the driving of trucks off-road or on provisional un-paved roads. Drivers deliver RMC throughout the working day and occasionally carry out equipment checks and maintenance tasks.

Generally, drivers have to repeatedly drive the same route until the total requested quantity of RMC is delivered.

With regard to the driver, a healthy male adult was chosen to participate in this field study. The subject was 49 years old, and his height and weight were 1.85 m and 120 Kg. His body mass index was 35.1 kg/m^2. He had experience as a truck driver at the concrete plant for more than 20 years and reported that he did not have current pain, nor a history of WMDs. These were the main reasons for his selection. With respect to the posture groups classified in Appendix A of ISO 2631-5, the driver's posture was posture group 3. The anthropometric characteristics of the driver and the posture group 3 were used as input to the model. The vehicle used in the case study was a MAN TGS 35.420 which seat has a passive air suspension seat. This type of seat is an manufacturing standard for off-road vehicles used in construction sector [59]. It should be noted that the seat type significantly influences the transmission of WBV to the driver. In fact, previous research has shown that the seat suspensions designs have a significant effect on the vibrations transmitted to vehicle operators [60]. Therefore, the characteristics of the vehicle, the seat and the operator should be taken into account when carrying out the analysis.

Based on this information, a measuring strategy was defined in order to characterise the vibration exposure in the activity under analysis. For this purpose, monitoring of the exposure to WBV in real concrete supply routes were measured in order to provide enough data to be representative of the exposure in different conditions and surfaces. The routes analysed comprise a variety of representative real surface conditions for this activity. The measurement was carried out in both urban and non-urban areas.

A tri-axial accelerometer (SV38, SVANTEK) was used to measure the acceleration transmitted to the seat pad. The instrument enables the sampling of the experimental acceleration with a frequency of 6000 Hz in each direction: fore-to-aft (x-axis), left-to-right (y-axis) and buttocks-to-head (z-axis). The equipment meets the ISO 8041 [61] and ISO 2631 requirements for measurements. A GPS logger was also used to simultaneously recorded the time and position of the vehicle (Fig. 2).

Following a measurement campaign, the acceleration and travel velocity were obtained in representative situations on different surfaces to characterise the exposure. From this data, the parameters described in section 3.1. have been calculated. The results obtained are shown in Table 3.

4.2. Stage 2: Raster calculation and routing process optimisation

Open Source Data [62] have been used for the creation of the GIS database of the study area. The area layout given by the GIS database, that includes information of type of roads, obstacles, and type of area, is used to create the *cost dataset raste*r as the stated Stage 2 defined in section 3.2.

4.3. Stage 3: Data visualisation and decision making

Based on the origin and destination dataset (Fig. 3), the *optimal route* can be calculated. The result obtained in this case is shown in Fig. 4.

On the basis of the route obtained in GIS, the methodological framework automatically calculates the value of the parameters used in the optimisation process. In this case, the estimated time to complete the route is 259.9 s, the length of the route is 2.99 km, and the $A(8)_r$ is 0.056 m/s^2.

As mentioned above, in addition to the route obtained with the criterion proposed in Stage 2 of the methodology, the fastest route and the shortest route have been calculated. Fig. 5 shows the *optimal route* obtained in the proposed methodology (in green), together with the fastest route (in red) and the shortest route (in blue) between the established origin and destination points. Table 4 shows the parameters associated with each of the routes.

As shown in Fig. 6, the *optimal route* minimises the parameter A(8) with a 10% decrease per path from the fastest route, and a 31% decrease from the shortest route, which has a high impact on the WBV exposure value. Although the shortest route has the shortest length, this is the most time-consuming and provides the highest A(8) value of the three routes. Regarding the fastest route, this is the one that requires the least time, but it is the one that takes the longest distance and provides a higher A(8) value than the one provided by the route obtained in the proposed methodology. Moreover, the results obtained in the illustrative

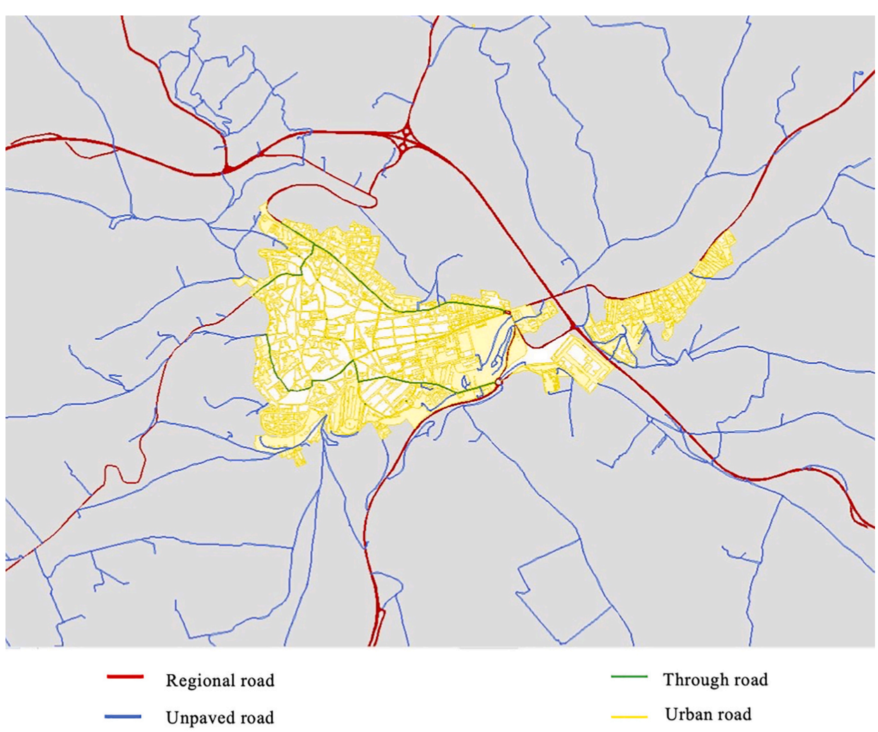

Fig. 2. Road network in the study area.

Table 3
Results obtained from the activity characterisation process.

Type of surfaces	$t_{1km,\ s}$ [s]	$A(8)_x$ [m/s^2]	$A(8)_y$ [m/s^2]	$A(8)_z$ [m/s^2]	VDV_x [m/s$^{1.75}$]	VDV_y [m/s$^{1.75}$]	VDV_z [m/s$^{1.75}$]	Max $S_{1km,\ s}{}^A$ [MPa]
Regional road	48.10	0.022	0.024	0.038	2.066	2.392	4.021	0.246
Through road	69.65	0.025	0.018	0.025	2.026	1.658	2.612	0.187
Urban road	120.69	0.025	0.018	0.021	2.020	1.322	1.858	0.112
Unpaved road	354.19	0.066	0.042	0.037	3.758	2.477	2.212	0.134
Off-road	809.86	0.143	0.089	0.065	6.329	4.411	3.379	0.193

Fig. 3. Origin and destination dataset.

case show that only minimising the time taken to make the travel, or the distance, does not guarantee that WBV exposure is minimised.

Furthermore, since the total distances travelled on each type of surface have been estimated, and the exposure characterisation has been carried out in the initial stage of the methodological framework, the VDV_r and the $S_r{}^A$ values associated with the *optimal route* obtained are determined automatically. In this case, the values are 3.9423 m/s$^{1.75}$ and 0.2419 MPa, respectively. In the case that the driver would have to travel 8 times the route in the working day to deliver the total volume of RMC ordered by client, the daily exposure values A(8), VDV y $S_d{}^A$are 0.159 m/s^2, 6.630 m/s$^{1.75}$ and 0.342 MPa, respectively. The daily values obtained are below the daily exposure limit values for vibrations (Table 1).

As mentioned above, the daily exposure values obtained can be used to monitor the life-time exposure history of the worker. In this sense, the values of $S_d{}^A$ obtained can be used to assess the adverse health effects related to the daily compressive dose for every disc level with the risk factor R^A. Since the risk factor R^A considers the year at which the exposure started and the duration of exposure in relation to the age of the exposed person, it is used to assess the long-term WBV exposure. In the case study analysed, the company states that the worker has 25 years of experience but does not provide specific data on exposure time periods (hours per day, and days per year) and the life-time exposure history.

5. Discussion

Nowadays, a large number of workers are exposed to WBV on a daily basis. Although in literature numerous studies have been published on safety management, the proposed GIS-based framework aims at reducing the gap arising on those problems related to WBV affecting construction industry drivers, such as concrete mixer truck drivers for example. The results obtained from the implementation of the proposed framework can contribute to increasing safety knowledge in the construction industry and encouraging the use of best practices to reduce WBV exposure. This framework provides to the safety manager some key information to perform an assessment of the short and long-term cumulative WBV exposure, as well as to establish a basis for further investigations on the PtD of routes.

The methodological framework proposed in this study shows how it is possible to use GIS systems for routing in order to minimise the WBV exposure, as well as other specific optimisation criteria, i.e., travel time. The level of WBV exposure associated with the activity performance by the worker and the different types of surfaces, as well as the

Fig. 4. Optimal Route (based on the optimisation criteria shown in Table 2).

topographical characteristics of the area and the roads, are taken into account. The methodology can be applied to any area for which the road network and the DEM map are available. Although generating the *cost dataset raste*r involves an initial effort in Stage 2 of the methodology, in the medium term it will allow the calculation of multiple routes between different origins and destinations according to specific *optimising criteria*.

Three consecutive methodological stages can be distinguished in the methodological framework. In Stage 1, an analysis of the activity characteristics is carried out and a measurement strategy is defined to ensure that the data obtained are representative of the different exposures. Based on this information, the WBV exposure and the position and velocity of the vehicle is measured in representative situations of each type of activity. Subsequently, in Stage 2, a GIS database containing the topographic morphology of the study area is created. It includes the road network available for travel, enriched with attributes coming from Stage 1 (WBV exposure and the travel time associated with the type of surface). From this data, raster files can be obtained for the creation of the cost raster dataset. The presence of obstacles (water bodies, buildings, etc.) or areas not suitable for vehicle travel (restricted access areas or slopes greater than 15%) are included in the cost raster dataset by assigning these cells a much higher value than neighboring cells. The provided raster-based approach allows to take into account off-road travel, which is very common in the construction and engineering sector. The raster cost dataset obtained, along with the origin and destination dataset, are used to determine the *optimal route* according to the *optimising criteria*. In Stage 3, the obtained route is displayed in the GIS software interface and the dose of WBV exposure, the length and the time taken to complete the route, is estimated.

In addition to the parameters set as optimisation criteria, the GIS framework provides the dose of WBV exposure associated to the route, i.e., $A(8)_r$, VDV_r y S_r^A. These values can be used as input to estimate the risk factor R^A according to ISO 2631-5:2018. R^A is used to assess the cumulative exposure of the worker to be assessed. Since WBV exposures can be affected by factors such as vehicle type, surfaces conditions (paved-road, unpaved road, off-road, etc.), anthropometric characteristics of the driver, seat type and tasks, these factors must be taken into account in the analysis. Thus, the proposed methodological framework should be applied on a specific case-by-case basis. Although the implementation of the proposed GIS-based framework requires an initial effort, the obtained results ensure the safety of the workers throughout their working life.

In summary, the proposed GIS-based methodological framework provides key information to ensure the safety of workers through the design of routes. The results obtained can be used to estimate the daily exposure and generate a database with the life-time exposure history of the worker. The implementation of the proposed methodological framework contributes to the assessment of WBV risk in the short and long term, as well as to the prevention of WMSDs. These objectives are aligned with two of the three main occupational health and safety challenges defined by the EU Strategic Framework on Health and Safety at Work 2014–2020 [63], such as addressing the challenge of ageing, and the prevention of work-related and occupational diseases. Moreover, it is an example of implementing the basic concept present in all European occupational health and safety policies [64]: the PtD, by eliminating or minimising the possible adverse health effects on workers in the initial stages of management and organisation of activities. Finally, it is possible to make the jobs more sustainable through the activity management process using the proposed methodological framework. Manage WBV exposure in order to prevent MSDs, since initial stages of management ensure that people can work until retirement age and have a good quality of life after retirement, which is one of the common challenges facing society nowadays [17].

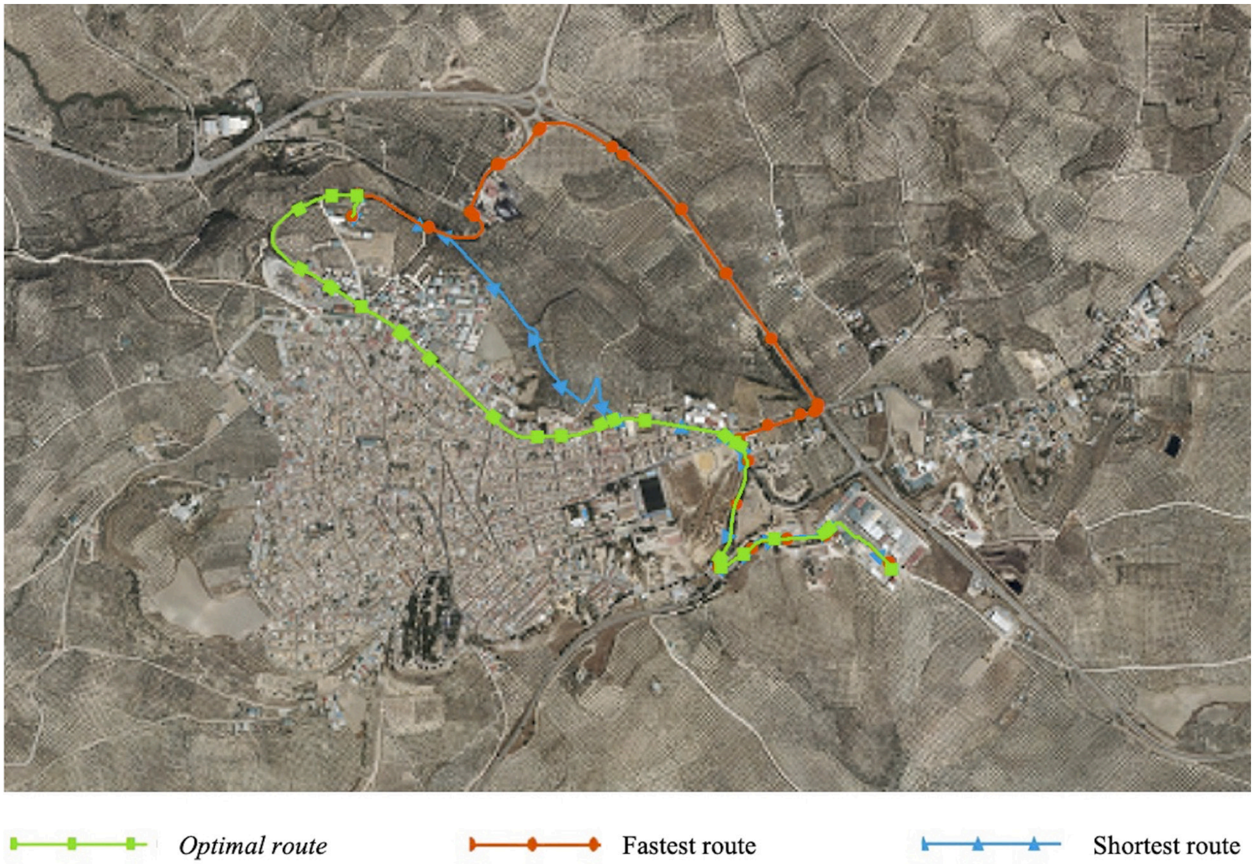

Fig. 5. Case study results.

Table 4
Case study parameter results.

Route	Time [s]	A(8) [m/s^2]	Length [km]
Fastest route (red)	243.8	0.063	3.31
Optimal route (green)	259.9	0.056	2.99
Shortest route (blue)	400.5	0.081	2.60

6. Conclusion

One third of the global population is dealing with WMSDs, with workers in the construction sector being among the most affected population. WBV exposure is one of the factors related to the development of WMSDs. With the aim of protecting workers' health, the European Parliament published the EU Directive 2002/44/EC about the minimum

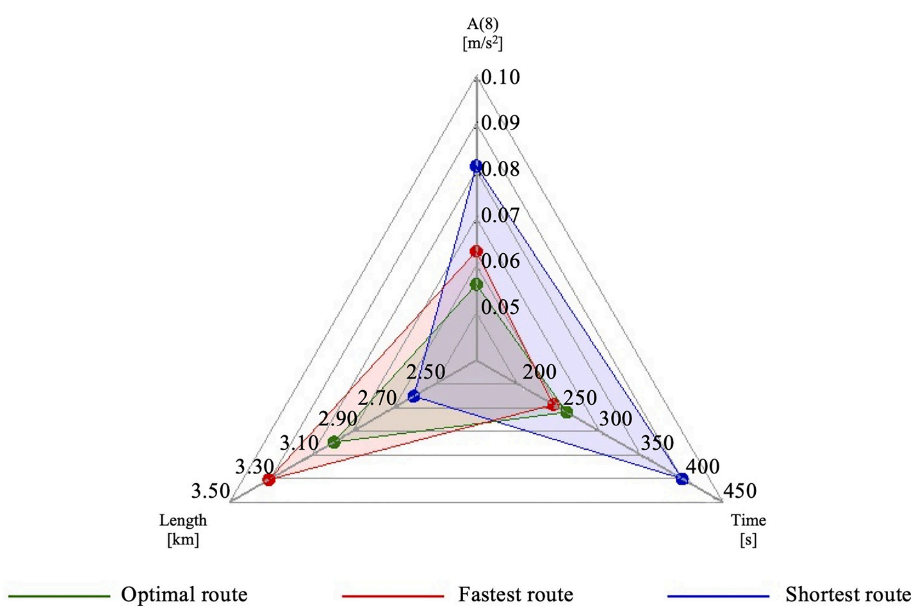

Fig. 6. Case study parameter results.

health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration).

In this context, the objective of this research was to develop a GIS-based methodological framework, which implement the assessment method stated in the EU Directive 2002/44/EC for the design of routes, and the automatic calculation of the WBV exposure dose value of workers.

In summary, from the results obtained, the following conclusions have been drawn:

- The implementation of the proposed methodological framework extends the safety management capabilities of WBV exposure in the route design process in a GIS environment. The model estimates the WBV exposure value associated with the route, as well as the time taken by the vehicle to travel the route and the distance travelled.
- The proposed model includes travel in off-road areas, facilitating the layout of routes in non-urban areas that require off-road travel. This type of off-road travel is very common in the engineering and construction sector during the execution of projects.
- The results obtained from the methodological framework provide key information to the safety manager in the decision-making process of activity design. In addition, the results obtained can be used to generate a database of the worker's life-time exposure history. This data can be used to apply the assessment methods to WBV exposure over the years, as defined in ISO 2631–5. Therefore, the safety manager can manage jobs not only by assessing the daily exposure, but also by assessing the consequences on the worker to exposure to WBV on a prolonged basis over the years. Therefore, the safety manager can manage jobs not only by assessing the daily exposure, but also by assessing the consequences on the worker of prolonged WBV exposure over the years.
- The methodological framework is flexible, i.e., it can be applied to any area as long as the road network and DEM file of the study area are available. While generating the framework may require some initial effort, once developed it can be used to calculate multiple routes.

Finally, the proposed GIS-based methodological framework is a tool for WBV exposure management whose implementation facilitates the management and assessment of WBV exposure with the main criteria of protecting worker's health. Minimising the impact of WBV exposure on workers' health will not only minimise the cost of work-related illnesses, but also improve individual workers' lives. This tool may be also combined with other criteria to achieve a comprehensive optimisation based on the real time route planning relying on traffic flow combined with WBV index, which could be of interest in other applications. A natural extension of the current work would involve the interlock with Internet of Things (IoT) devices and real time monitoring. This implies to link the changing conditions of the construction site with the proposed framework automatically, which is a long-term task. Therefore, the next step will be to further develop the framework in order to minimise the construction workers exposure to WBV while maximising productivity in a real time optimisation process.

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Declaration of Competing Interest

The authors have no financial disclosures or conflicts of interest to report.

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Appendix A. Acronyms

aw - Frequency-weighted instantaneous acceleration.
A(8) - Daily vibration exposure according to the Directive 2002/44/EC.
$A(8)_{i\ 1km,\ s}$ - Daily vibration exposure in the i axis due to vibration exposure associated with travelling 1 km on s-th surface.
b - Age at which the exposure started.
B - Area of the vertebral endplate.
$c_{dyn,\ i}$ - Sum of peak compressive forces acting on the vertebral endplate.
DEM - Digital Elevation Model.
EAV - Exposure Action Value.
ELV - Exposure Limits Value.
k - Multiplication factor defined for each axis.
$l_{d,\ s}$ - Total distance of the route over the s-th type of surface.
LCP - Least-Cost Path.
m - Denotes the m-th year.
n - Total number of operations implying worker exposition to WBV.
N_m - Number of exposure days per year m.
p - Number total of surfaces in the r-th route.
PtD - Prevention through design.
r - Denotes the r-th route.
R^A - Risk Factor according to the standard ISO2631-5.
rms_w - Root mean square of the weighted averaged acceleration.
rms_{iws} - Root mean square of the weighted averaged acceleration in the i axis due to vibration exposure on the s-th surface.
RMC - Ready mix concrete.
S^A - Dynamic compressive stress of the lumbar spine due to vibration exposure to WBV operation.
S_j^A - Dynamic compressive stress of the lumbar spine due to vibration exposure to operation j.
$S_{1km,\ s}^A$ - Dynamic compressive stress of the lumbar spine due to vibration exposure associated with travelling 1 km on the s-th surface.

S_d^A - Equivalent daily compressive dose.
$S_{stat,\,m}^A$ - Mean value of the compressive-decompressive force divided by the area of a vertebra endplate B (mm^2) in year m.
$S_{u,\,m}^A$ - Ultimate strength of the lumbar vertebra for a person of age $(b+m)$ years
t - Total number of routes driven during the working day.
$t_{1km,\,s}$ - Time taken to travel 1 km over the s-th surface.
t_{dj} - Time period of the daily vibration exposure to operation j.
$t_{d,\,s}$ - Exposure time on the s-th type of surface.
t_{mj} - Time period over which S_j^A has been measured.
$t_{m,\,s}$ - Measurement time on the s-th surface.
t_r - Total time taken by the vehicle to perform the r-th route.
T - Time duration of the measurement
T_{exp} - Daily duration of exposure to the vibrations.
T_{meas} - Measurement period.
T_0 - Reference duration of eight hours.
$\overline{v_s}$ - Mean velocity to travel 1 km over the s-th surface.
vdv_w - Vibration dose value of the weighted averaged acceleration.
vdv_{iws} - Vibration dose value calculated as the fourth power of the acceleration time history in the i axis due to vibration exposure on the s-th surface.
VDV - Vibration dose value according to the Directive 2002/44/EC.
$VDV_{i\ 1km,\,s}$ - Vibration Dose Value in the i axis due to vibration exposure associated with travelling 1 km on the s-th surface.
WBV - Whole-Body Vibration.
WMSDs - Work-related musculoskeletal disorders.

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