Occupied Wheelchairs and Scooters

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Percentiles, included percentage, and most-compact spaces

(DRAFT)

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Occupied Wheelchairs and Scooters: Percentiles, percentage inclusion, representatives and most-compact spaces

This paper discusses the diversity of results that occur from percentile analyses of complex entities such as occupied wheelchairs and scooters. It discusses the problems and the purpose of percentiles analysis and the need for an alternative "percentage inclusion" approach in relation to most-compact spatial analyses for wheelchairs and scooters.

The need to identify several representative wheelchairs and scooters with which to determine the most compact spaces for wheelchair and scooter manoeuvring is explained, as is the irrelevance of positing an n^{th} percentile footprint for this purpose.

Introduction

The Commonwealth of Australia recently commissioned research into the minimum size of spaces required for wheelchairs and scooter use in buildings[i]. The purpose of the research was to inform the development of the imminent Disability Discrimination Act Premises Standard[ii], and the revision of Australian Standard 1428.1 [1,iii]. The goal of the research was to identify the "90th percentile footprint" representative of wheelchairs and scooters currently in use in the Australian community. The footprint was required to include the wheelchair and scooter drivers, i.e. to be the footprint of occupied vehicles.

The current wheelchair space provisions in AS1428.1 are derived from research carried out 20 years ago by Bails [2] and are based on the "A80 wheelchair"[iv]: ostensibly an 80th percentile wheelchair footprint. The sample size upon which the "A80" wheelchair is based ranges from 40 to 72 for various parameters[v].

The new research was brought about by the need to determine whether there were any changes in types and sizes of wheelchairs and scooters since the time of the A80 research by Bails, and was required to incorporate a larger research sample size[vi], and a larger percentile value to ensure that a greater and more representative proportion of users of wheelchairs and scooters in the community would be catered for, thus achieving greater consistency with the DDA.

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[i] The research is being undertaken by Hunarch Consulting.

[ii] The Australian Commonwealth Disability Discrimination Act (DDA) Premises Standard is being developed in order to harmonise the DDA with the Australian Building regulations, the Building Code of Australia (BCA).

[iii] AS1428 is called up by the BCA. It is also called up in the current DDA Transport Standard and will be called up by the proposed DDA Premises Standard.

[iv] The term used by Bails was "A80 wheelchair", denoting the shape of a wheelchair that was 'representative of 80% of all "adult wheelchairs then in use'.

[v] The sample size for overall length and width parameters was 72, however, for track width it was only 40. Track width, insofar as it establishes the ground contact points of drive wheels, is critical for establishing key radial parameters in the geometry of wheelchairs and scooters manoeuvring. Hence, the sample size for seeking to establish a manoeuvring model is effectively only 40. Bails' research largely pre-dated the advent of scooters and therefore deals only with wheelchairs.

[vi] The sample size achieved for the Commonwealth project was 560.

There are inherent problems in expressing a research goal as establishing a "90th percentile footprint". One problem is that, for a population of geometrically complex entities like occupied wheelchairs and scooters, it is practically impossible for a percentile to be applied to several discrepant defining parameters that will yield an equivalent percentage inclusion of entities for the population.

The other problem is that there is no single shape that is geometrically representative in any sufficient way of occupied wheelchairs and scooters generally. A number of shapes are required.

Another difficulty of percentile analyses is that results are not absolute: they are relative to the analytic procedures and methods used. Hence, no one result is necessarily more correct than another, simply more compelling or appropriate.

There is a very simple solution to the first two problems. It is to use a percentage inclusion as the criterion, not a percentile, and to use several actual wheelchairs and scooters as the representatives, not a single model of them.

Percentiles and multivariate entities

What is a percentile?

Percentiles are commonly used in anthropometrics and ergonomic research and are expressed in terms of a single percentile such as the "90th percentile", or in terms of two percentiles such as "between the 5th and 95th percentiles".

The purpose of a single percentile reference is to deal with all except the largest cases, whereas the purpose of a dual percentile reference is to deal with all except the smallest and largest cases. For the determination the smallest manoeuvring space for 90% of occupied wheelchairs and scooters, it is a single percentile that applies and is the one that is discussed here.

A "percentile", or more accurately, "percentile point"[3] is merely a positional designation that indicates that to one side of the point there are a certain number of entities which, including the entity at the point, comprise an equivalent percentage of all of the entities (i.e. n% are included by an *n*th percentile). It also denotes that all entities within this included percentage are the same size or smaller than the entity at the percentile point.

The frustration of percentiles

The outcomes of percentile analyses can appear confusing and erratic.

The confusion occurs when, for a group of discrepant entities, results that are typical of parameters individually are expected of parameters jointly. For example, the rectangles illustrated as groups A to C in Table 1, have identical parameters, length and width, but differ in the way the parameters relate to each other. The average values for the parameters remain the same in all cases, however the results of percentiles analyses vary dramatically.

For all groups, the value associated with the 75th percentile point for length is 9[vii].

For Group A, three of the four rectangles (75%) have a width of 5 or less[viii]. Because width increases evenly with length (the frequencies and class intervals are the same), the percentage of rectangles included by the 75th percentile point for *both* length *and* width is the same as the percentage included by the 75th percentile point

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[vii] The real upper limit for length at the 75th percentile point for length is 9.5

[viii] The real upper limit for width at the 75th percentile point for is width is 5.5

for length *or* width only. In other words, the percentage inclusion for rectangles having both length and width the same size or smaller than the length and width at their 75th percentile point remains at 75%. In this instance, using a single percentile to denote an equivalent percentage inclusion is valid. This is not the case for the other groups.

Grp. A.	Grp. B.	Grp. C.	Group D.
l w	*l w*	*l w*	*l w h*
10 x 6	10 x 3	10 x 4	10 x 3 x 4
9 x **5**	**9** x 4	**9** x 6	**9** x 4 x 6
8 x 4	8 x **5**	8 x 3	8 x **5** x 3
7 x 3	7 x 6	7 x **5**	7 x 6 x **5**

Ave. *l* for all grps. = 12. Ave. *w* & *h* for all grps. = 9

Table 1

For Group B, widths decrease evenly with length. After sorting width, the width at the 75th percentile point remains at 5. However, the percentage inclusion for rectangles having length *and* width the same size or smaller than their size at the 75th percentile point is reduced to 50%

For Group C, widths vary unevenly with length. The width at the 75th percentile point is still 5, and the percentage inclusion for rectangles with length *and* width the same size or smaller than their size at the 75th percentile point also remains the same at 50%. However, the greatest length of the included rectangles (8) is less than the greatest length included by the 75th percentile value for length.

If the number of parameters defining the entities is increased to three, as shown for Group D, the percentage inclusion for entities having *all* parameters at or below their 75th percentile points is reduced to only 25% i.e. entity “8 x 5 x 3”. In this instance also, the included entity has parameters that are smaller than their size at the 75th percentile point.

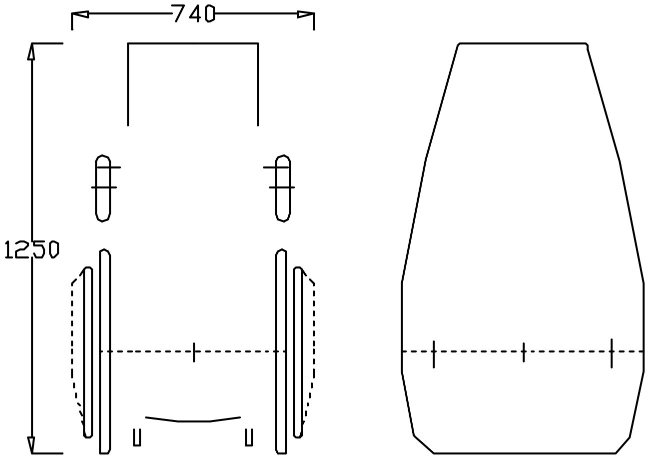

Figure 1: Bails’ A80 Wheelchair

The diagram on the right is a boundary shape. The drawings include knuckle clearance.

The diversity of outcomes of percentile analyses can be further illustrated using the wheelchair data of Bails, and Seeger et al[4].

Bails and Seeger et al

For Bails’ data, the 80th percentile value for length is found to be 1250mm and 740mm for width[ix], the same as that reported by Bails (see Fig 1 below). In other words, 80% of occupied wheelchairs have a length of 1250mm or less, and 80% have a width of 740mm or less. This does not

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[ix] Only 16 of Bails sample has been used because, even though the data for the samples of 40 to 74 for the different parameters are tabulated by Bails, they are not all identified and therefore cannot be correlated. In other words, only 16 occupied wheelchairs are identifiable with more than one parameter value, and even these have no more than three parameters, hence a fuller replication of Bails’ analysis is not possible.

mean however that the 80% of occupied wheelchairs included for length are necessarily the same as the 80% included for width.

Two conclusions can be drawn:

a. The percentage inclusion of occupied wheelchairs that are *either* no longer than 1250mm regardless of width, *or* no wider than 740mm regardless of length is 100%, and:

b. The percentage inclusion of occupied wheelchairs that is no longer than 1250mm *and* no wider than 740mm will probably be reduced below 80%. In fact, the reduced percentage is just below 70%.

If there were a perfect correlation between length and width (e.g. if width increased proportionately with length), the two sets of 80% of occupied wheelchairs would be one and the same, as would therefore be the 20% of wheelchairs excluded. In actuality it is found that there is virtually no correlation between Bails' length and width. Hence, very few of the 20% of occupied wheelchairs that are longer than the 80th percentile for length are the same as those that are wider than the 80th percentile value for width (in fact, only 6% approximately of all wheelchairs are found to be longer than their 80th percentile values for length *and* width).

Expressed differently, the 80% of wheelchairs included for length includes just below 70% of all wheelchairs that are no wider than the 80th percentile for width; and the 80% of wheelchairs included for width includes just below 70% of all wheelchairs that are no longer than the 80th percentile value for length. In other words, the 80th percentile excludes over 30% of occupied wheelchairs, not 20%. These results are for a two-parameter analysis.

If a third parameter is used in the analysis, such as wheelbase[x], the included percentage for the occupied wheelchairs reduces further to just over 60%. The 80th percentile values for length and width happen to remain the same at 1250mm and 740mm respectively, however the overall size reduces because the size of the third parameter, wheelbase, reduces from 970mm for the two-parameter analysis to 760mm for the three-parameter analysis.

If a fourth parameter is included, say, proportion of length and width[xi], the percentage inclusion reduces to below 60%. Again, the overall size also reduces.

Similar outcomes occur with the data of Seeger et al. In a replicated analysis using their data, after discounting scooters, and occupants under 18 years of age[xii], the 80th percentile values are found to be 1240mm for length and 760mm for width, and the percentage inclusion of occupied wheelchairs having length *and* width at or below their sizes at their 80th percentile point is 68%.

If a third parameter is used for analysis, wheelchair-only width, the included percentage is reduced to 59% and overall length and width reduces. If a fourth parameter is included, length-width proportion, the included percentage further reduces to 53%, and the overall length and width also further reduces. If six parameters are used, the included percentage is even further reduced to 40%.

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[x] Wheelbase is only relevant to scooter manoeuvring, not wheelchair manoeuvring. However it is used here to illustrate the effect of increased number of parameters in analysis.

[xi] This ratio does not necessarily have any practical significance. It is used here solely for purpose of illustration in the absence a more relevant parameter from Bails' data (nevertheless, a similar ratio is identified later as a key parameter in "The geometry of wheelchairs and scooters in use").

[xii] The Commonwealth research involved people 18 years old and older. The age correlates of Bails' dataset are not known.

These results illustrate the inherently diminutive effect of percentiles when applied to parameters jointly, and the correspondence of the diminution with increase in the number of parameters. Similar effects have been reported in relation to the design of aircraft crew stations[5].

The problem of percentiles

The foregoing discussion highlights the fundamentally problematical nature of percentile analyses for complex entities such as occupied wheelchairs and scooters.

Percentiles are only applicable to single parameters (i.e. they are univariate). For planar shapes and volumetric forms, this poses a problem because at least two parameters are required to define planar shapes, and at least three to define volumetric forms (planar and volumetric forms are multivariate). With more complex morphologies, more than two or three parameters will be required.

The problem of percentiles has been reported by others in relation to the design of chairs[6], flight-crew helmets[7], car interiors[8,9], and aircraft cockpits[10]; and the "anthropometrics of disability"[11].

Percentiles can of course be applied to individual parameters of multivariate entities. However, if the entities have to be selected or analysed using more than one parameter and if, for the group of entities, one or more of the parameters increases in, say, size as another or others decrease, and if also at various rates, the resulting percentage inclusion of entities for the group will be reduced below the percentage value designated by the percentile. The size of the largest entity within the included group will also tend to be reduced.

With increasing numbers of parameters required to define entities, further reductions tend to occur as the number of parameters increases. The identification of relevant parameters, and the number of them, is therefore critical in percentile analyses.

The purpose of percentiles: identifying representative entities

The purpose of percentiles analysis for the Commonwealth research is to identify wheelchairs and scooters that are the largest of the included percentage, i.e. the representative wheelchairs and scooters. And, the purpose of this is for these representative wheelchairs and scooters to be used in simulated driving trials to determine the most compact space requirements.

Single parameter: longest or widest wheelchair

As already noted, a single parameter can be used to identify a representative of a complex entity, however, the choice of parameter can lead to very different results, and identification of an appropriate representative entity can therefore be critical. For example, we have seen that, for the data of Seeger et al., the value of length at the 80th percentile is 1240mm and the value of width is 740mm. The overall width of the wheelchair that has a length of 1240mm has an overall width of 880mm. In contrast, the wheelchair that has an overall width of 760mm has a length of 1750mm.

The choice of the representative wheelchair clearly leads to different results. For passageway width, the relevant parameter would be overall width of the wheelchair, and the representative wheelchair would therefore be one selected on the basis of its width matching the value of width at the percentile point. However, for lifts in buildings, length could be a more appropriate parameter, in which case the representative wheelchair would be one chosen on the basis that its length matches the value of length at the percentile point.

Joint parameters: longest and widest wheelchair

For building spaces such as lifts, it is more likely that both length and width parameters should be considered, in which case, the representative wheelchair would need to be chosen for correspondence of its length and width with the length and width at the percentile point. However, as has been demonstrated, this will give a spurious result because the number of wheelchairs accommodated will be less than the percentage inclusion corresponding with the percentile value.

Single compound parameter: largest wheelchair

For the rectangles of group A in Table 1, in terms of individual parameters, it is easy to identity a largest rectangle, i.e. a rectangle that has the greatest length of the included rectangles, and the greatest width. However, for groups B and C it is not. Similarly, for the wheelchairs of Seeger et al.: the longest is 1240mm long and 880mm wide, and the widest is 1750mm long and 760mm wide. The identification of a representative rectangle for these cases in terms of both parameters is therefore difficult.

One could adopt an hypothetical largest rectangle, defined by the value of length and width at their percentile point. This is actually the way that Bails' A80 wheelchair has been defined. However, because percentiles analysis deals only with real entities, for purposes of analysis we would need to include a "dummy" entity within the group. The effect of this would be to increase the included percentage and to tend to increase the size of the parameters at their percentile point.

Alternatively, one could posit an enclosure, defined by the greatest of each of the parameters for the included entities, i.e. the most compact "accommodating space". However this is a different matter, the validity and usefulness of which is discussed later.

One could also devise a composite or compound parameter by which to identify the largest of the included entities, e.g. a product or a quotient of the parameters (e.g. area or hypotenuse for rectangles). However, this would be invalid unless all entities within a group of entities were analysed in terms of the same composite parameter.

Table 2 shows the sorted areas of the rectangles for groups B and C. The 75th percentile value for area for both groups is 40. Because the percentile analysis relates to a single parameter for the whole of groups B and C, the percentage inclusion corresponds with the percentile point, i.e. 75%. This is a correct percentile analysis.

However, the outcomes are quite different to those for Group B and C sorted for length and width in Table 1. In Table 3, For Group B, the length and width at the 75th percentile point for area (8 and 5), correspond with the largest length and width in the included percentage for Group B in Table 1. In contrast, for Group C, the length and width at the 75th percentile point for area (10 and 4), do not correspond with the largest length and width for the included percentage for Group C in Table 1, or with the individual 75th percentile point sizes for length and width.

Group B	Group C
l w a	l w a
7 x 6 = 42	9 x 6 = 54
8 x 5 = **40**	10 x 4 = **40**
9 x 4 = 36	7 x 5 = 35
10 x 3 = 30	8 x 3 = 24

Table 2

For the wheelchairs of Seeger et al., the one corresponding with the 80th percentile for area has a length of 1140mm and a width of 800mm, in contrast to the values of 1240mm and 760mm at the 80th percentile points for length and width.

However, using a compound parameter such as area in order to correctly identify an entity with a percentile value for that parameter is unhelpful if it is the constituent parameters in which we are really interested. For example, knowing the identity of the wheelchair of Seeger et al that corresponds with the 80th percentile for area, and therefore its length and width (1140mm x 800mm), will not give us the size of, say, a lift that will accommodate 80% of wheelchairs. In fact, there is only a 44% inclusion if the lift is 1140mm long and 800nmm wide. On the other hand, the maximum length and width accommodated by the 80th percentile for area is 1450mm and 860mm In other words, the lift would need to be 1450m x 860mm.

The identification of an entity to represent a parameter is only valid for subsequent analyses if those analyses are in terms of that parameter. This is why it is so important to correctly identify relevant parameters for use in percentiles analyses.

Representative shapes and accommodating spaces

The foregoing discussion conveys the diversity of results that can be obtained for very simple shapes. With more complex shapes that require a greater number of parameters to define them, such as occupied wheelchairs and scooters; larger group sizes as achieved for the Commonwealth research; and a greater variation of frequencies and class intervals, the outcomes of percentile analyses can be even more diverse. How then, can a representative shape for complex others be established?

Representative Shapes

If a representative shape means the shape that is the embodiment of the essence of other shapes, then there can be no such thing as a representative shape of, say, a circle, triangle and rectangle. Nor is there likely to be such a shape for complex irregular shapes such as occupied wheelchairs and scooters.

Common Boundary Shape

A practical alternative definition of representative shape is a shape that most compactly encloses or accommodates other shapes, i.e. a common boundary shape. The common boundary shape might not, and in the case of wheelchairs and scooters, typically does not closely resemble the shapes it bounds.

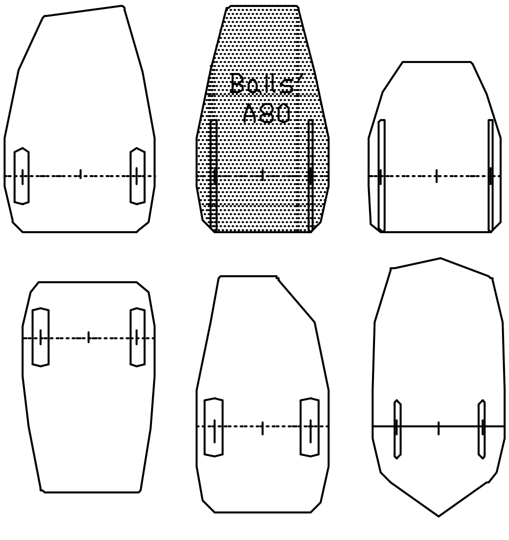

Figure 2: Variations in wheelchair shapes

Common boundary shapes require specification of a common point or line by which to align the constituent shapes. For example, the most compact common boundary shape that accommodates a circle, triangle and rectangle, can be found by aligning the shapes at their centroids. However, this boundary shape will not necessarily be the same as the one formed if the alignment points are on the circumference of the circle, the apex of the triangle and the middle of one side of the rectangle. Nor will the common boundary shape be the same if the constituent shapes are asymmetrical (e.g. if the triangle were a scalene triangle). This is a critical issue for the Commonwealth research because asymmetry is a characteristic of occupied wheelchairs and scooters.

The specification of a common alignment point or line will be determined by the purpose for which the analysis is being conducted. Therein lies one reason why there can be no single footprint for wheelchairs and scooters: there will be as many “footprints” as there need to be different alignment points or lines. For example, the most compact common boundary shape for wheelchairs that need to be aligned at feet or footplates, or at knees as applicable to spaces under bench tops, will be different to the shape of the boundary for a lift enclosure. In this case, the most compact common boundary shape will have an alignment point that approximates to the centroids, or various centre points of the wheelchairs.

This is illustrated in Figures 2 and 3. Figure 2 shows the Bails’ A80 wheelchair, together with outlines of typical others. The one at the bottom left is a front-wheel drive wheelchair.

Figure 3 shows common boundary shapes formed by superimposing the individual boundary shapes. Shapes 1, 2 and 3 are formed by the alignment of the wheelchairs at their right wheel, left wheel, and mid-axle point respectively. Shapes 4 and 5 are formed by the alignment of the wheelchairs at their rear-most points and front-most points respectively. Clearly, the form of the common boundary shape differs with the alignment point.

A method of establishing a common boundary shape of wheelchairs and scooters relative to a particular datum is to overlay the key boundary points, or the boundary shapes of each occupied vehicle using a CAD program and then to join all of the outermost points. However, there may be little need to do this: outer-most boundary points, or a partial boundary shape may b all that is required.

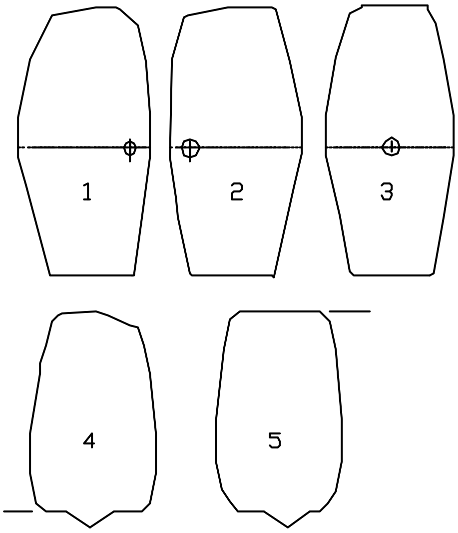

Figure 3: Composite boundary shapes

Accommodating Space

For research into the spatial needs of wheelchairs and scooters, it is the shape of the most-compact accommodating shape in which we are we interested. The most-compact accommodating space can be regarded as the space which most compactly encloses the most-compact common boundary shape. For stationary wheelchairs and scooters, the two shapes are synonymous. However for moving shapes, they are not.

For moving shapes, details of the overall common boundary shape can be superfluous. For example, if we wished to determine the most compact accommodating space for a 360 degree rotation of a rectangle and a symmetrical triangle (e.g. equilateral or isosceles), the space would have a radius equal to the greatest of the distance for each shape from their common point (the centre of rotation) to whichever point is most distant from it. The definition of the circle merely requires one linear parameter for definition, no shape information.

The definition of the most compact accommodating space requires the identification, not of common boundary shapes, but of key boundary points and, ultimately, of wheelchairs and scooters that each represents a key boundary point and corresponding key parameter.

Which parameters for wheelchairs and scooters?

Where the purpose of percentiles analysis is to select representative wheelchairs and scooters for use in simulations to determine most-compact spaces, the parameter or parameters that are used for selection should obviously be of a relevant spatial nature.

There are two criteria for the selection of parameters: the attainment of representativeness, and correspondence with most compact space.

In terms of representativeness, there appears to be no inherent statistical reason for choosing one spatial parameter over another, provided that it yields the required percentage inclusion. However, the choice of parameters is important in determining the most compact spaces.

Notwithstanding the seeming unimportance of parameters for purposes of statistical representativeness, it seems consistent for the same parameters relevant to least space formulation to also be used for purposes of initial selection. It would appear arbitrary if wheelchairs were excluded because they were larger than the size at the percentile for a parameter having little spatial significance, but smaller than the size for another parameter having greater spatial significance. Whilst this would be a case of one person's loss being another person's gain (remembering that the percentage inclusion is preserved), the distribution of such losses and gains is probably for various other reasons most desirably done on the basis of the most spatially relevant criteria.

The importance of identifying relevant parameters has already been discussed in relation to lifts and the data from Seeger et al. The following example further illustrates the importance of identifying parameters that are the most spatially relevant as selection criteria.

Twenty rectangles having length and width are shown in Table 3. If a task were to describe the smallest rectangle that would accommodate 90% of the rectangles, one could simply calculate the respective areas, sort them and identify the area at the 90th percentile point. It is found that the rectangles excluded are "2x39" and "1x38".

However, if the task were to describe the smallest circle that would accommodate the rotation of the rectangles about one of their corners, the relevant parameter to use would not be area, but their diagonal length. After a percentiles procedure, it is found that the rectangles excluded are now "20x21" and "19x22".

In other words, using rectangles chosen for area to determine the smallest circle will mis-identify the representative rectangle.

l		*w*
1	X	**40**
2	X	**39**
3	X	38
4	X	37
5	X	36
6	X	35
7	X	34
8	X	33
9	X	32
10	X	31
11	X	30
12	X	29
13	X	28
14	X	27
15	X	26
16	X	25
17	X	24
18	X	23
19	X	**22**
20	X	**21**

Table 3

The geometry of wheelchairs and scooters in use

Wheelchair and scooters in use can be analysed is terms of stationary states, linear motion, and rotational motion of which there are two types: circular and helical.

Three types of parameters are required to define accommodating spaces for stationary occupied vehicles: width, length, and key boundary points or partial boundary shapes.

For linear motion the key parameter is width

For circular rotational motion of wheelchairs there are a number of identifiable key centres of rotation. They are: radii from the mid-axle to the front and the back, and radii from each wheel to the front and back. In addition, because occupied wheelchairs and scooters are asymmetrical about an axis perpendicular to the drive wheel axle, separate radial parameters are required from both drive wheels. Hence, there are six radial parameters.

These radial parameters are identifiable as key parameters because, mid-axle rotations are the most compact rotations possible within a bounded space; and either-wheel rotations are the most compact possible rotations around objects. The sizes of these radial parameters are intrinsic to the occupied wheelchairs and can therefore be obtained from knowledge of the occupied wheelchairs.

For circular rotational motion of scooters, there is only one key radial parameter: the radius from a point determined by the maximum steering lock of the scooter. The size of parameter is intrinsic to occupied scooters and can therefore be obtained from knowledge of the occupied scooters.

For helical rotational motion of wheelchairs and scooters, because this is the result of continual variation of the location on the drive wheel axis of the centre of rotation, there is no easily quantifiable parameter. In many circumstances, the shapes of the quadrant boundaries (the quadrants formed by the drive wheel axle and an axis perpendicular to it) in relation to spatial constraints determine helical motion. For this purpose therefore, a very approximate measure of the quadrant boundary shape is its proportion, i.e. the ration of, say, the forward radius and width.

Overall length has no role in the geometry of linear and rotational motion geometry. Overall length is relevant in the determination of the accommodating spaces for stationary wheelchairs and scooters, however for this purpose, length can be defined as the sum of length to the front from the drive-wheel axis and length to the rear.

Castor wheels play no primary role in the geometry of wheelchair

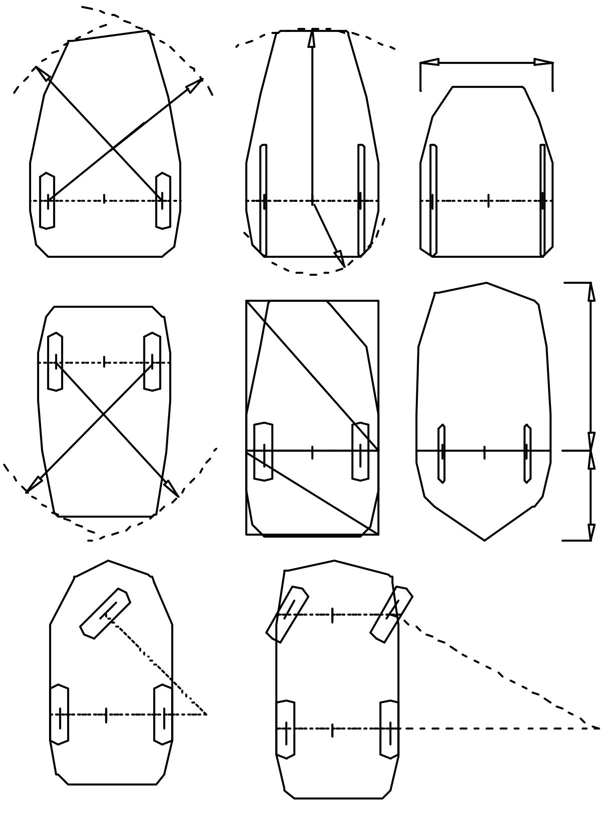

Figure 4: Spatially relevant parameters

manoeuvring, (although their possible counter-splaying during reversing manoeuvres should be taken into account). In contrast, the steering wheels of scooters do play a primary role.

In summary, for wheelchairs there are at least thirteen key parameters, and for scooters there are at least six key parameters required to define stationary states, linear motion, circular rotational motion, and helical rotational motion, all of which are inherently or can be related to the axis through the drive wheels.

How sufficient are the identified parameters?

Rotational movement is always related to the axis through the drive wheels, and all possible centres of rotation will be on this axis. The rotation can of course be about an infinite number of points on that axis varying, for wheelchairs, between the mid-axle point and infinity and, for scooters, between the point determined by the maximum steering lock and infinity. Rotational manoeuvres also typically involve a series of separate rotations having different centres of rotation (relative to the wheelchair or scooter), or continuously varying centres of rotation.

Apart from the quantifiable radial parameters associated with the identifiable key centres of rotation, the fact that it is impossible to quantify radial parameters associated with the infinite number of other centres of, including for helical rotations is probably relatively unimportant. This is because, as previously explained, the purpose of the percentiles analysis is to select the representative wheelchairs and scooters to be used in simulated driving trials. It is the driving trials that are used to describe the least space requirements for wheelchair and scooter manoeuvring[xiii].

It is believed that the parameters defined above account for nearly all of the significant variations between wheelchairs and scooters, and that additional variations in relation to other radii will therefore add negligible value. It is for this reason that the infinite number of possible centres of rotation and radii and the impossibility of quantifying them is not a practical problem.

Representative wheelchairs and scooters

Because it is highly improbable that any wheelchair or scooter will have all parameters the same size as that at a particular percentile point, there will need to be several representative wheelchairs and scooters, each one representing a key parameter of travel and manoeuvring geometry such that the parameter corresponds in size to that at the percentile point.

Given so many parameters; given the complication this creates for percentile analysis; and given that percentile analysis can only proceed in relation to single parameters, what statistical procedure should be adopted to identity the representative wheelchairs and scooters?

Which percentiles analysis?

There is a very simple analytic approach: the use of “percentage inclusion”. In other words, instead of seeking to identify an *n*th percentile representative, a representative of each of the several parameters is identified at whatever percentile value for each

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[xiii] Because the determination of the most compact spaces for wheelchair travel and manoeuvring is to be found from a driving simulation computer program, such a program obviously needs to replicate a choice of any one of the infinite number of possible centres of rotation. The computer program used for the Commonwealth research is capable of doing that

of them gives the n% inclusion. The value of the percentiles does not matter, provided that it yields the desired percentage inclusion.

The validity of the approach has been affirmed elsewhere, including by Whitestone and Robinette[12], and in US Military Standard 1472 [13].

Two approaches are discussed here, both of which are relevant to the Commonwealth research: percentage inclusion applied to actual parameters; and percentage inclusion applied to derived parameters using principal components and factor analysis.

Percentage inclusion and actual parameters

This is a joint-parameter percentile analysis that achieves the desired percentile inclusion by increasing the values associated with the parameters. There are two approaches: increasing the value of the percentile, or increasing the values of the parameters (e.g. increasing length and width[xiv]).

For the second approach, the size of the parameters at the percentile is identified and, by trial and error, the sizes are successively increased until the required percentage inclusion is achieved.

Increasing the size of the parameters is laborious and gives the appearance of arbitrariness, and is best avoided in favour of the percentiles increment approach.

The percentage inclusion method can be illustrated by reference to Bails' data. It has already been shown that, if three parameters are used, the percentage inclusion is approximately 60%, not 80%.

On the basis of a three-parameter analysis of Bails' data, using overall length, width, and the proportion between them, increasing the percentile value from 80% to 90% in expectation that this will yield a 80% inclusion, the representative sizes become 1360mm for length and 760mm for width, and the achieved included percentage is 81%. The sizes are greater than the 1250mm x 740mm of Bails' A80 wheelchair.

If the third parameter is wheelbase, not length/width ratio, the same analysis yields a length of 1390mm and width of 760mm. This highlights earlier comments about the importance of identifying the most relevant parameters (the length/width ration is believed more relevant than wheelbase because it approximates to a radial parameter that is more approximately relevant to wheelchair manoeuvring).

If all four of the parameters above are used, and the percentile value increased to 92.5, a percentage inclusion of 81% is once again achieved, however the representative length and width now become 1450mm and 760mm.

Similarly, it has also been shown that if three parameters are used for the analysis of the data of Seeger et al, the percentage inclusion is found to be below 60%.

If the percentile value is increased from 80% to 90%, the percentage inclusion increases to just over 80%, corresponding with a maximum length of 1310mm and maximum width of 790mm (compared with 1250mm and 760mm). As with Bails ' data, using an increased percentile value achieves the target percentage inclusion. It also increases the corresponding sizes of parameters.

[xiv] Length is used, instead of a more relevant parameter because more relevant parameters are unavailable from Seeger's data: it is simply to illustrate the outcomes of percentile analyses.

If six parameters are used: overall length, wheelchair width, overall width, length-to-width ratio[xv], wheelchair height and head height, an 80% inclusion is achieved if a percentile of 95.5 is applied to each of the parameters. The corresponding maximum overall length becomes 1410mm and the maximum overall width becomes 820mm. The results for all parameters are shown in Table 5.

It is evident that for any given percentage inclusion, an increase in the number of required parameters necessitates an increase in the value of the percentile to be used for analysis. For a very small number of parameters, the percentile increment technique is simple and effective, however with an increasing number of parameters, the process becomes laborious. In this case, principal components and factor analysis can be a better technique.

Percentage inclusion and derived parameters: principal components and factor analysis

Principal components and factor analysis are statistical techniques for multivariate entities or properties that enable the identification of a much smaller number of derivative parameters (principal components or factors). It is based on correlations between the parameters, the number of the components being determined by the extent to which the selected components correspond with most of the variation between the original parameters. The conventional guidance on the number of components or factors to be used is the “eigenvalues greater than one” test or the graphical “scree” test. However, in analyses for this paper

```
Seeger et al
Factor analysis, rotated
(Stata vers.7.0)
.  factor length3 width5 width6 lwratio wcht hdht
if(vehtypecomb<=2 & age>=1)
Factor    Eigenvalue  Difference  Proportion  Cumulative
1         1.994       0.265       0.517       0.517
2         1.73        1.412       0.449       0.966
3         0.318       0.325       0.082       1.049
4         -0.01       0.028       -0          1.047
5         -0.04       0.109       -0.01       1.037
6         -0.14       .           -0.04       1
Rotated Factor Loadings (Varimax rotation)
Variable  1           2           3           Uniqueness
length3   0.373       0.922       0.079       0.004
width5    0.655       0.189       0.346       0.415
width6    0.993       -0.05       0.03        0.011
lwratio   -0.41       0.91        0.018       0.005
wcht      0.044       0.27        0.404       0.762
hdht      0.243       0.012       0.423       0.762
. score fr1 fr2 fr3
          Scoring Coefficients (based on rotated
          factors:1 scoring not used )
Variable  1           2           3
length3   0.764       0.563       1.621
width5    -0.05       -0.03       0.397
width6    0.445       0.032       -1.69
lwratio   -0.74       0.54        -1.87
wcht      -0.01       -0.03       0.268
hdht      -0.01       0.003       0.29
. _pctile fr1 if(vehtypecomb<=2 & age>=1),p(91.75)
. gen fr1_pu=r(r1)
. _pctile fr2 if(vehtypecomb<=2 & age>=1),p(91.75)
. gen fr2_pu=r(r1)
. _pctile fr3 if(vehtypecomb<=2 & age>=1),p(91.75)
. gen fr3_pu=r(r1)
. tabstat length3 width5 width6 lwratio wcht hdht
if(vehtypecomb<=2 & age>=1 & fr1<=fr1_pu
& fr2<=fr2_pu & fr3<=fr3_pu), stat(n max)
stats     length3     width5      width6      lwratio  wcht   hdht
N                179         179         179      179    179    179
max             1415         790         800     2.07   1275   1434
```

Table 4

[xv] As previously noted, length-to-width ration has no spatial relevance and is used simply to illustrate the outcomes of percentile analyses.

and related research, it has been found that including a component or factor with an eigenvalue just below 1.0 sometimes gave greater clarity to the structure of the components or factors.

If only one principal component is identified, a simple percentiles analysis can proceed in relation to that component. However, if there are two or more, then a percentage inclusion strategy as described above can be used.

There are three similar forms of analysis that can be carried out: principal components analysis, factor analysis, and principal components factor analysis. Furthermore, with the factor analysis and principal components factor analysis, a statistical procedure called rotation can be applied. Rotation can yield a simpler structure of principal components or factors and hence more interpretable results[14]. Consequently, there are at least seven possible procedures that can be adopted. None of these procedures is necessarily better than the other, and each can give slightly different results. The reason for the differences is the relative weighting that the procedures inherently give to the parameters. The judgment will then be required as to which is the most appropriate one, for which there may be no obvious or absolute guidelines: simply a matter of selecting the procedure that seems the most ‘sense’[15] or one that gives the ’most appealing structure’[16].

Seeger et al: n=224									
Parameter	Individual 80th p’tile values	Size at Percentile							
		Results of % inclusion	Results of PCA, FA & PCFA						
			PC	PCF	PCF/r	PCF/rp	F	F/r	F/rp
O'all length	1240	**1410**	1415	1340	1340	1340	1340	**1415**	1340
O'all width	680	**820**	890	860	850	850	880	**800**	790
W'chr width	760	**715**	790	790	710	710	800	**790**	790
l/w ratio	1.9	**2.1**	2.06	1.97	2.07	2.07	2.02	**2.07**	2.07
Wchr ht	960	**1210**	1275	1366	1364	1364	1193	**1275**	1364
Head ht	1300	**1392**	1434	1415	1415	1415	1434	**1434**	1415
Pcntile val.	80	**95.5**	92	88.5	88.5	87.75	92.5	**91.75**	90.5
% Incl.	80	80	80	80	80	80	80	80	80
No of Components, Factors			3	2	2	2	3	3	3

Table 5

The procedures can be illustrated in relation to the data of Seeger et al. For this purpose, the same six parameters already used will be used here. The height parameters have been included for purposes of illustration in the absence of other parameters relevant to the planar geometry of wheelchair manoeuvring. Wheelchairs and occupants over aged 18 years and over are included in the analysis. The purpose of the analysis here is to ascertain the least overall length, width and height that will accommodate the 80% of occupied wheelchairs.

The analysis is comprised of the following steps:

1. Principal component and factor analyses, with and without rotation
2. Identification of components and factors

3. Calculation of percentile values for the components or factors required for 80% inclusion.
4. Identification of the actual parameters (length, width etc) corresponding with the 80% inclusion of the components or factors (the derived parameters).

As shown in Table 5, there are seven sets of varying results, all indicating that percentile values have had to be increased to those ranging from 88.5 to 92.5 to achieve a percentage inclusion of 80, and that the value of all parameters at their respective percentile points has increased compared to the values at their 80th percentile points.

After reviewing the pattern of factor loadings for each of the seven procedures, the one that is found to give the most distinct structure is factor analysis using principal factors and varimax rotation, as shown in Table 3. Unsurprisingly for our example, the association of the highest factor loadings (shown in bold in Table 3) with the original parameters tells us that there are three distinct derived parameters: length, width and height.

Trial-and-error percentile calculations to achieve the 80% inclusion for the factors are then carried out and, once the percentile point value has been identified, the values of the actual parameters are established, as shown in Table 4

Because there are at least seven procedures that may need to be used, and that successive testing for percentage inclusion may require several attempts, principal components and factor analysis can be laborious, although not as much as the percentage inclusion procedure using actual parameters and if there are a large number of actual parameters.

Comparing the foregoing results of percentage inclusion using actual parameters with results using derived parameters, it can be seen that there are differences between them. As for the choice between the various principal components and factor analyses, so also for the choice between percentage inclusion applied to actual parameters or derived parameters: there are no absolute guidelines. In reality for this example, because there are so few parameters, there is little need for a derived parameters procedure.

Discussion

Reconstituting the parameters: composite models

If the purpose in identifying representative occupied wheelchairs and scooters is to select those to be used in manoeuvring trials, the question is begged as to why, for greater efficiency, a single representative is not used for simulated manoeuvring. That is, a composite model comprised of wheelchairs selected for spatially relevant parameters whose values correspond with a particular percentile and that yield a desired percentage inclusion for the wheelchairs and scooters collectively.

To ascertain the required width of linear travel spaces, because only one parameter is involved, we do not require a composite entity, simply the widest entity at the percentile point. Furthermore, we do not require shape information or simulation of travel to ascertain the required width: all that is required is knowledge of the width. A composite entity is therefore not wrong, but it is superfluous.

To ascertain the size and shape of spaces to accommodate stationary wheelchairs and scooters, it is possible to establish a common boundary shape. However as explained, there will need to be as many common boundary shapes as there are different purposes. If the definition of the most compact rectangle is all that is required, then knowledge of the overall length and width is all that is needed: shape information is superfluous. It should be noted that the most compact rectangle however, will be larger than the most compact space accommodating the common boundary shapes. Shapes for stationary entities are very different to those accommodating rotational manoeuvres.

For spaces accommodating rotational manoeuvres, it is also possible to establish composite models, providing that there are as many models as there are required centres of rotation. As already indicated, there are two key types of centres-of-rotation that are significant in most-compact rotational manoeuvres: mid-axle and either wheel rotations. For each of these rotations, it is possible to establish a composite model. However, in manoeuvring generally, there will be numerous other centres of rotation, the choice of which is infinite. As also earlier explained, the adoption of the two key types of centres of rotation for purposes of identifying representative entities is a pragmatic one: identifying representative entities on the basis of these key parameters will yield sufficiently representative entities in terms of radial manoeuvres. However, for manoeuvring trials, we would need to create models for all centres of rotation. The infinite number of other centres-of-rotation additional to the key ones, and given that in reality the choice of such centres-of-rotation is a freely available relative to the navigational judgments of wheelchair and scooter drivers, the establishment of composite models is practically unattainable.

Rotational manoeuvres typically also entail helical rotations. Because helical rotations entail a continuously changing centre of rotation and, again, given that in reality the choice of such centres-of-rotation is a freely available one, the infinite number of possible centres of rotation, and the relationship between them renders the establishment of a composite model impossible in practical terms.

Even if, in addition to the key centres of rotation at mid-axle and either wheel, a composite model were established in relation to some other centre of rotation, it is found that, whilst the space that accommodates travel by a composite model will accommodate travel by each the constituent wheelchairs, a space that accommodates travel by each of the constituent wheelchairs will not accommodate travel by the composite model. In other words, using a composite model may result in space that is larger than necessary.

The foregoing is illustrated in Figures 5 and 6. Figure 5 illustrates three hypothetical wheelchairs. For our purposes, assume that the wheelchairs are three of several hypothetical wheelchairs that each represents key parameters and whose parameter values correspond with, say, the 94.5th percentile, and that collectively, all of the wheelchairs represent 90% of the population from which they are drawn. Assume also that the three wheelchairs represent the forward mix-axle radius, overall width and rear mid-axle radius at the 94.5th percentile. Wheelchair A is an electric front-wheel drive type, Wheelchair B is an electric rear-wheel drive type and Wheelchair C is a manual rear-wheel drive type. In

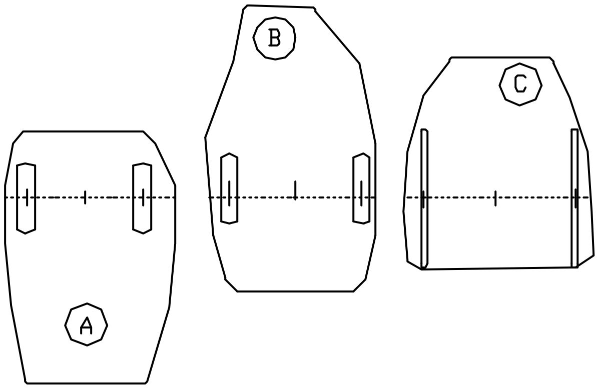

Figure 5

other words, Wheelchair A represents the 94.5th percentile rearward radius; B represents the 94.5th percentile forward radius, and C represents the 94.5th percentile width.

Figure 6 illustrates radial travel paths with the same inner circumference of 433 mm. Diagram 1 shows a composite of the three wheelchairs aligned on their drive wheel axes, with at a common centre of rotation corresponding with the centre of the inner circumference, and so that all wheelchairs are just touching the inner circumference. The width of the radial travel path for the composite model is seen to be 967 mm, determined by Wheelchair A. Diagrams 2, 3 and 4 show the radial paths for each of the wheelchairs traveling helically. It can be seen that the greatest path width is 874 mm, determined by Wheelchair C, and that this is the width that will accommodate all wheelchairs, as shown in Diagram 5.

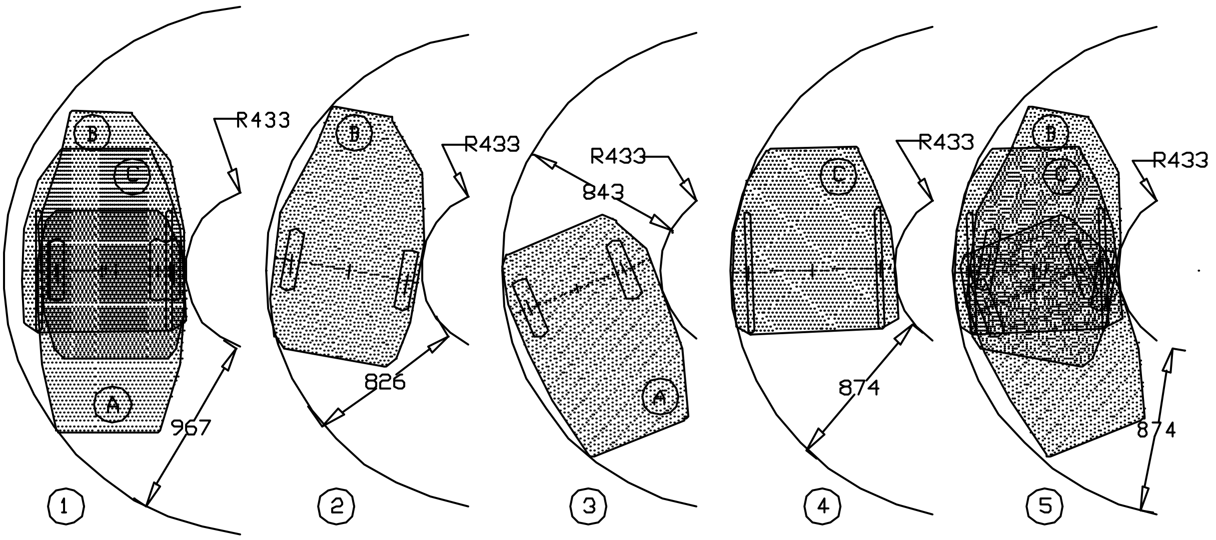

Figure 6

It is therefore more accurate, in terms of most compact spaces, to use individual representative wheelchairs and scooters, not composite models.

Classes

For purposes of ascertaining minimum linear travel width, and formulating spaces for stationary wheelchairs and scooters, wheelchairs and scooters can be treated collectively.

However, for rotational motion, they cannot. Wheelchairs are able to rotate about points anywhere along their drive wheel axis between the drive wheels, whereas scooters are not. Seeger et al found that scooters are generally longer and narrower than wheelchairs. To include scooters with wheelchairs for determining a representative entity would yield one that was neither representative of wheelchairs nor scooters. Hence, accurate space formulation also requires that wheelchairs and scooters be treated separately: it would make no sense to generate spaces for rotational manoeuvres of wheelchairs if the wheelchairs parameters were partly determined by scooter sizes. Conversely, it would make no sense to formulate travel paths for scooters on the basis of parameters that were partly determined by wheelchair sizes.

The same issue applies to the various drive-types of wheelchairs (rear-wheel, mid-wheel or front-wheel). For example, given the significant differences in forward and rearward dimensions of rear-wheel and front-wheel drive wheelchairs, as illustrated in Figures 2 and 5, if there is a significant number of front-wheel drive wheelchairs included by the value of a percentile point from a sample of rear- and front-wheel drive wheelchairs, a joint rather than separate analyses of drive wheel types will yield a representative entity for all of them that is unrepresentative of each of them, and that will therefore compromise the accuracy of most-compact space formulations. For example, if a single entity is used to represent all types, some rear-wheel drive wheelchairs may be excluded in terms of their forward dimensions, whilst manoeuvring spaces may need to be larger by virtue of rearward dimensions.

The need for separate analyses in terms of drive types is illustrated in Figure 6. It can be seen that there is a difference in radial travel width between the front-wheel drive wheelchair, Wheelchair A, and the rear-wheel drive wheelchairs, wheelchairs B and Wheelchair C.

With regard to electric and manual wheelchairs, Seeger et al found that occupied manual wheelchairs were typically wider than occupied electric wheelchairs. Seeger et al did not find any significant difference in length between manual and electric wheelchairs. However, a very large proportion of their sample was comprised of people who lived institutions, and who were over the age of 65. If a larger proportion of the sample were drawn more broadly, it is possible that significant differences would have been found for length as well as width.

The need for separate analyses in terms of the means of propulsion (manual or motorised) is illustrated in Figure 6. It can be seen that there is a marked difference in radial travel width between the two rear-wheel wheelchairs, Wheelchair B (826 mm) and Wheelchair C (874 mm). By chance, the difference between the widths (not indicated here) of the two hypothetical wheelchairs is virtually the same as the 41mm found by Seeger et al.

For greater representativeness and spatial accuracy, the three drive-wheel types, and the means of propulsion should be considered separately.

The Use of Percentiles Designations

In view of the inherently problematical nature of percentile doe complex entities, percentile designations in documents should only be used in relation to an overall entity if there is a corresponding percentage inclusion for that overall entity. For example, in the earlier rectangles examples, there are only four instances where a term such as “75th percentile rectangle” could legitimately be used: group A in Table 1, and groups B and C in Table 2.

By comparison, in relation to Group B of Table 1, to designate a rectangle “9x5” the “75th percentile rectangle” would be misleading because the included percentage is only 50% and because no rectangle has a size that is “9x5”.

The review of Bails’ A80 wheelchair data shows that the A80 wheelchair actually caters for far less than 80% of the wheelchair using population sampled by him, with the A80 dimensions being up to 140mm too short and 20mm too narrow for his sampled population. Similar results are found with the data of Seeger et al.

The A80 designation in Bails’ report and in AS1428 is therefore incorrect and misleading. However, it should be noted that this does not necessarily discredit the actual final results of Bails, or the corresponding dimensional requirements in AS1428. Bails’ final results were derived from manoeuvring trials and incorporated margins for driving inaccuracy. It is possible that the margins were not solely margins for driving inaccuracy as intended by Bails, but in actuality also margins for the inaccuracy of the hypothetical model that Bails used. Nevertheless, the use of the A80 designation casts some doubt on the reliability of the current AS1428 in relation to wheelchair space provisions.

For the data of Seeger et al, there is also need for any extrapolation of their results to be appropriately made in terms of percentiles analyses. The analysis of the data of Seeger et shows that, for 80% of occupied wheelchairs, overall length is at least 1310mm and overall width at least 790mm, compared with the 80th percentile length and width found by them of 1240mm and 760mm.

To avoid similar confusion, any percentile references in the future DDA Premises Standard and revised AS1428 should be on the basis of a correspondence of the percentile with an equivalent percentage inclusion or otherwise, on the basis that any non-correspondence be obvious and explained.

It would be far simpler and appropriate for the DDA Premises Standard and AS1428 to be predicated simply upon a percentage inclusion.

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