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Distribution of cocaine on banknotes in general circulation in England and Wales

C.G.G.Aitken[a,*], A. Wilson[b], R. Sleeman[c], B.E.M. Morgan[c], J. Huish[c]

[a] *University of Edinburgh, School of Mathematics and Maxwell Institute, Peter Guthrie Tait Road, Edinburgh, EH9 3FD, UK*

[b] *University of Durham, Department of Mathematical Sciences, Lower Mountjoy, Stockton Road, Durham, DH1 3LE, UK*

[c] *Mass Spec Analytical Ltd., Golf Course Lane, Filton, Bristol, BS34 7RP, UK*

Abstract

A study of the quantities of cocaine on banknotes in general circulation was conducted to investigate regional variations across England and Wales. No meaningful support was found for the proposition that there is regional variation in the quantities of cocaine in banknotes in general circulation in England and Wales.

Keywords: Cocaine, Banknotes, Regional variation, Mixed effects models

1. Introduction

A study of the quantities of cocaine on banknotes in general circulation was conducted to investigate regional variations across England and Wales. The study was conducted in response to a 2014 court ruling [*R. v. Rashid and others*, [T20147216] (19th January 2015)] and to review the findings of a similar study reported on in 2007 [6]. In the 2007 study, tests were carried out which did not find evidence that the region from which the banknotes in general circulation came has an effect on the quantities of drug found [6].

The study reported in [6] is a very good investigation of the factors influencing the contamination of UK banknotes with drugs of abuse. Seven possible factors were studied, one of which was a dummy variable. The work of Mass Spec Analytical Ltd. (MSA) received support in a court ruling in 2007 *Director of the Assets Recovery Agency v Jackson and others*[2007] All ER (D) 149 (Nov): 'Nor is it now in dispute that the MSA database is representative of banknotes taken from banks located in the United Kingdom' (para. 185) ; and 'references to data from the Association of Payment Clearing Services show[ing] "weekly cash payments within the UK account for approximately 20% of the total cash in circulation which represents significant mixing over time. In addition, cash entering the banking system and other major organisations such as supermarkets, is collected on a daily basis and sent to sorting centres" ' (para. 188).

It will always be possible to argue that a particular level of a particular factor specific to a particular case has not been studied. Thus, not every city in the UK has had notes sampled from it for the study in [6]. This may be seen as a failing when applying the data to a particular city. A possible rebuttal of a suggestion of failure would be to take a sample (in some way) from a population deemed relevant to a particular case at the time of the police investigation. Such a procedure is open to other criticisms of irrelevance:

- Area: the area from which the sample was taken may be too large or may be too small; there is no criterion to determine the correct area. However, it is noted in [6] that "notes originating in one area may rapidly end up in another part of the country, and the banknotes handled by drug dealers will mix in the system, precluding a stable geographical population of banknotes" (p. 169).

*Corresponding author, School of Mathematics, The University of Edinburgh, UK.
Email address: cgga@ed.ac.uk (C.G.G.Aitken)

- Relevance of type: the relevance of the type of source of the banknotes to a particular case is difficult to determine and hence it is easy to argue irrelevance. For example, suppose the seizure was made in a casino, therefore it could be said the training set should be from a casino (or the same casino). Alternatively, suppose the seizure was made in an area of dockland, therefore it could be said the training set should be from an area (the same area) of dockland. Many of the banknotes in MSA's training sets are taken from banks, for which they have been criticised. In the same paragraph of [6] quoted in the immediate point above, it is also noted that "[f]ew businesses, especially in areas where there are high crime rates, carry large quantities of cash on their premises for lengthy periods of time; banknotes will pass into the banking system, from where they are sent to regional sorting centres" (p. 169). This statement provides a strong argument that banks are the best place from which to take samples.

Notwithstanding the above explanations of the good quality of the database used by MSA, the database came under severe criticism in *R. v. Rashid and others*. For example, '[i]t is a database of pure convenience' (page 31C) or '[t]he assertion that notes from banks are typical is not supported by any evidence and is illogical' (page 31G). The court also wanted to 'have seen a much, much, more recent paper, much more objectively scrutinised, dealing very closely with the database . . .'. It is as an answer to that last comment that the study, to which the results reported here refer, was conducted.

The timeliness of the data in [6] was criticised in the ruling. The study [6] was published in 2007 and refers to data collected from 2004 onwards. Such data may be thought out of date in the context of a case reported on in 2015 (and assumed to be of crime committed in 2014). However, in a report written in response to the Sheffield ruling MSA note that

"MSA's database is unquestionably the largest such database in the world, comprising the examination of over one hundred thousand individual notes (at the time of writing, 118,951 sterling banknotes have been examined), with a value of over one and a half million pounds (at the time of writing £1,710,315). Together with the Bristol data, today's database is massive when compared to the database which was deemed '... sufficient for comparisons safely to be based on it ...' (para. 27) in the Court of Appeal Case of *Compton and Compton* [2002] EWCA Crim 2835 (and supported in *Benn and Benn* [2004] EWCA Crim 2100, paras. 44 and 45). The *Compton* ruling also stated 'we apply our own common sense to conclude that the range and weight of MSA's database is sufficient for comparisons safely to be based on it.' (para.27 of *Compton and Compton*). Interestingly, in *Compton*, the argument was put forward that '... no samples had been taken from London, or from any of the larger northern cities' (para. 26), and that there was a concentration on Lloyds Bank, precisely the argument being put forward today against a database which is now ten times larger than at the end of 2002, and includes many more locations. Whilst it is true to say that this is a small proportion of notes in general circulation, it is unfair and inaccurate to say that it has no statistical significance, without deferring to statistical experts to offer an opinion."

Thus, the database has been kept up to date and has grown considerably in size since the time to which [6] refers.

The court in *R. v. Rashid and others* was also concerned about the semi-quantitative nature of the data. The method of thermal desorption combined with tandem mass spectrometry is considered to be semi-quantitative because no method has yet been published to extrapolate the intensities of the ion transitions detected to the absolute quantity of drug present on the banknote [2]. Despite this, it is still possible to use the data obtained in a statistical analysis because comparisons can be made between the intensity of ion transitions detected on different samples of banknotes. These transitions provide a proxy for the amount of cocaine, sufficient for a meaningful statistical analysis. Two examples of such a statistical analysis which seek to determine the evidential value of cocaine on banknotes are described in [7] and [8]. The training data for these two studies were obtained from samples of English and Scottish currency obtained from a variety of police force areas and locations around the UK; see Tables 1 and 2 in [7]. A large number of the samples were taken from the Bristol area.

2. Data collection

2.1. Sampling procedure

The purpose of the study reported here is to consider the variation in the quantity of cocaine contamination on banknotes in general circulation in England and Wales. This will help answer a question often raised in court. To perform this study, samples of banknotes from different regions in England and Wales were required. This section discusses the procedure used to select these samples.

Following discussions with experts at the Bank of England, it was learnt that more than 75% of all banknotes issued are circulated via automatic telling machines (ATMs), the rest goes to banks, Post Offices and other outlets. Money is paid by businesses into banks, and this is typically returned to one of approximately $20-25$ cash redistribution centres within England. Certain larger retailers also send money directly to these centres. At the centres, money is sorted into three categories; *A-fit*, notes which are suitable for redistribution via ATMs, *B-fit*, notes which are suitable for use at branches of banks or the Post Office, or *Unfit*, notes which are weeded out and sent back to the Bank of England centres at Debden and Leeds for processing and destruction. An increasing proportion of banknotes are distributed via ATMs and *B-fit* notes correspondingly represent a decreasing proportion of redistributed cash. The redistribution centres distribute banknotes (sometimes via a number of cash-in-transit centres) directly to security companies which replenish ATMs, and to banks and other outlets. Money received at High Street bank branches from local businesses is unlikely to be paid out over the counter in that same branch, although there may be local variations. Instead it is likely to be sent to a redistribution centre for sorting.

For this study, access to Unfit notes (those returned for destruction to redistribution centres for England and Wales) was requested. It is not known whether or not banknotes continually build up contamination every time they pass through the banking system, or whether they reach an equilibrium state whereby the amount of drug abraded off is equal to the amount deposited, or whether some other explanation needs to be invoked for the quantity of drugs on the notes. However, it is reasonable to assume that older notes are likely to be the most worn, and therefore most likely to be declared *Unfit*, and it is also reasonable to assume that older notes are likely to have had the most exposure to 'environmental contamination' with cocaine. Therefore, use of data from these notes as representative of levels of cocaine in general circulation will be favourable to the defence in any court case. Banknotes were requested from each of eight redistribution centres. These notes also represent a source of banknotes with a good geographical spread across England and Wales in terms of area in which they last circulated, as suggested by experts at the Bank of England. The proportions of the denominations of the notes were chosen so as to reflect the proportions of different denominations in circulation. Only eight cash redistribution centres were used but these were geographically well spread out over England. After study of the results, it was clear that it was not necessary to use all 20 – 25 centres. There are no distribution centres in Wales and notes from Wales are sent to redistribution centres in England. The locations of the eight centres used were declared to the authors. The authors chose not to disclose the locations for security reasons but they include a wide spread of locations within England, covering the North, South, East, West, the Midlands and London.

2.2. Experimental design

In total, there were 32 sets of data forming the basis of the statistical analysis. These represent data from the eight cash redistribution centres. There are two samples of banknotes from each location and so sixteen samples in total. Ten samples of these sixteen have 120 notes, six samples have 125 notes. In total, 1,950 notes were analysed. Each of the sixteen samples was analysed twice, once by measuring the quantity of cocaine on the Queen's head end of the banknote and once by measuring the quantity of cocaine on the opposite end of the banknote. This gives $8 \times 2 \times 2$ sets of data. Each set of data was analysed by one of two analysts (A1 or A2) on one of two machines (C or F). The design of the experiment is shown in Table 1.

This design is different from that described in [6]. In [6], banknotes were collected from various outlets in accordance with a particular experimental design. For this investigation we were fortunate to be given access to notes from wholesale cash redistribution centres. Notes from these centres are much more representative of notes in general circulation than notes gathered from a few randomly chosen outlets around Great Britain or as part of the study in [6].

Table 1: Experimental design for the analysis of banknotes in general circulation taken from eight distribution centres, identified as $1, \ldots 8$ with two samples a and b from each centre. There are two analysts $A1$ and $A2$. There are two instruments F and C. The end at which a note is analysed is denoted 1 or 2.

Location	Sample	End	Analyst	Machine	No. notes
12924	a	1	$A1$	C	120
12924	a	2	$A2$	F	120
12924	b	1	$A2$	C	120
12924	b	2	$A1$	F	120
12925	a	1	$A1$	C	120
12925	a	2	$A2$	F	120
12925	b	1	$A2$	C	120
12925	b	2	$A1$	F	120
12926	a	1	$A1$	C	120
12926	a	2	$A2$	F	120
12926	b	1	$A2$	C	120
12926	b	2	$A1$	F	120
12927	a	1	$A1$	C	125
12927	a	2	$A2$	F	125
12927	b	1	$A2$	C	125
12927	b	2	$A1$	F	125
12928	a	1	$A1$	C	125
12928	a	2	$A2$	F	125
12928	b	1	$A2$	C	125
12928	b	2	$A1$	F	125
12929	a	1	$A1$	C	120
12929	a	2	$A2$	F	120
12929	b	1	$A2$	C	120
12929	b	2	$A1$	F	120
12930	a	1	$A1$	C	125
12930	a	2	$A2$	F	125
12930	b	1	$A2$	C	125
12930	b	2	$A1$	F	125
12931	a	1	$A1$	C	120
12931	a	2	$A2$	F	120
12931	b	1	$A2$	C	120
12931	b	2	$A1$	F	120

Cocaine measurements are obtained using thermal desorption combined with mass spectrometry. Further details of this process can be found in [5]. Raw measurements consist of a count of the intensity of the $304 \to 105$ ion transition at each scan of the mass spectrometer. Using the peak detection algorithm in [7], [8], peaks are identified in these raw measurements, where each peak corresponds to the insertion of a banknote into the thermal desorption unit of the mass spectrometer. These peaks are then integrated, to give a peak area for each end of each banknote. This peak area is a measurement of the quantity of cocaine on each end of the banknote. The data are transformed to log peak area for the statistical analysis in this paper.

3. Data analysis

The data are analysed using a mixed effects model with the function lme4 within R. A good description of the model and its use within R is available in [3]. The response variable is the log peak area for the cocaine ion transition $304 \to 105$. There are several explanatory variables, known as covariates. As described in [3]

> Parameters associated with the particular levels of a covariate are sometimes called the *effects* of the levels. If the set of possible levels of the covariate is fixed and reproducible the covariate is modelled using *fixed-effects* parameters. If the levels observed represent a random sample from the set of all possible levels then *random effects* are incorporated in the model.

The models investigated considered variables corresponding to the analyst, the location and the machine as fixed-effects. The purpose of the study is the investigation of variation in measurements of quantities of cocaine on banknotes in general circulation across the area of interest, taken here to be England and Wales. The variable *location* is the variable of interest in the investigation. There are two other possible sources of variation in the measurements. First, the two analysts may have slightly different techniques in analysing the notes (i.e. one could pass notes through the thermal desorption unit more quickly than the other). Second, the two machines may give slightly different readings. Variation amongst different denominations was not investigated. The previous study [6] found insufficient evidence of variation amongst denominations to consider it of relevance. There is no evidence to suggest this situation has changed in the intervening period.

The quantity of cocaine contamination on both the Queen's head end and the opposite end of each banknote was measured and so each banknote appears in the dataset twice. In the statistical analysis it is assumed that there is no systematic difference in the quantity of drug between the two ends of a note. As a result, the two measurements for each note may be treated as repeated measurements. We would expect the variance between notes in the dataset to be bigger than the variance within notes and so a term to account for *Note* must be included in the model to account for this difference.

There are two samples from each location. As with *Note*, there may be a difference in the variance within a sample and the variance between samples, so the inclusion of *Sample* as a variable in the model was investigated. Both *Sample* and *Note* are treated as random effects. The two samples represent random samples from the set of all possible samples of notes from their location. The notes may also be treated as random effects as they are assumed to be randomly chosen from all the notes at that location. Each note occurs within one and only one sample; the notes are said to be *nested* within the sample from which they were selected for analysis.

It is of interest to study the effects on measurements of the quantities of cocaine of differing sources (locations) for the banknotes after account has been taken of the analyst taking the measurement and the machine on which the measurement was made. Nine models were fitted and compared using the goodness-of-fit measures Bayes Information Criterion (BIC) and Akaike's Information Criterion (AIC). The results are given in Table 2.

4. Results

Two measures of goodness-of-fit are used: Bayes Information Criterion (BIC) and Akaike's Information Criterion (AIC). Both maximise log likelihood functions with penalties for the numbers of parameters estimated in the model;

the more parameters in the model, the better the fit is expected. A good description of the use of AIC and BIC for model interpretation is given in [4]. Individual values of AIC and BIC are not interpretable as they contain arbitrary constants and are much affected by sample size so the values are rescaled by subtraction of the minimum value AIC_{min} and BIC_{min}, respectively, from each of the other values. Thus, consider a comparison of M models ($M = 9$ here), the differences $\Delta_{Ai} = AIC_i - AIC_{min}$ and $\Delta_{Bi} = BIC_i - BIC_{min}$ are noted, for $i = 1, \ldots, M$, so when $i = min$, $\Delta_{Ai} = \Delta_{Bi} = 0$. The transformations $\exp(-\Delta_{Ai}/2)$ and $\exp(-\Delta_{Bi}/2)$ can be normalised such that they sum to 1 and then treated as relative likelihoods [1]. Thus:

$$w_{Ai} = \frac{\exp(-\Delta_{Ai}/2)}{\sum_{i=1}^{M} \exp(-\Delta_{Ai}/2)}, \text{ and } w_{Bi} = \frac{\exp(-\Delta_{Bi}/2)}{\sum_{i=1}^{M} \exp(-\Delta_{Bi}/2)}, \qquad (1)$$

for AIC and BIC, respectively.

Table 2: Two measures of goodness-of-fit, Akaike's information criterion (AIC) and Bayes' information criterion (BIC) for nine models of quantity of cocaine on banknotes in general circulation. Small values are good.

Model	BIC	AIC
1. Analyst, Location, Machine, Sample, Note	7279.110	7197.616
2. Analyst, Location, Machine, Note	7270.846	7195.622
3. Analyst, Location, Machine	8974.887	8905.931
4. Location, Machine, Sample, Note	8785.021	8709.796
5. Analyst, Machine, Sample, Note	7237.253	7199.641
6. Analyst, Location, Sample, Note	7521.012	7445.787
7. Machine, Sample, Note	8743.164	8711.820
8. Analyst, Sample, Note	7479.155	7447.812
9. Location, Sample, Note	8895.831	8826.875

The ordering of the models for AIC and BIC using the measures Δ_{Ai} and Δ_{Bi} and the associated relative likelihoods derived from (1) are given in Table 3. Using the BIC to compare models, Model 5 is clearly the preferred model as it has the minimum BIC and the remaining models have a relative likelihood of close to zero. When using the AIC, Model 2 has the smallest AIC, but Model 1 and Model 5 have non-zero relative likelihoods.

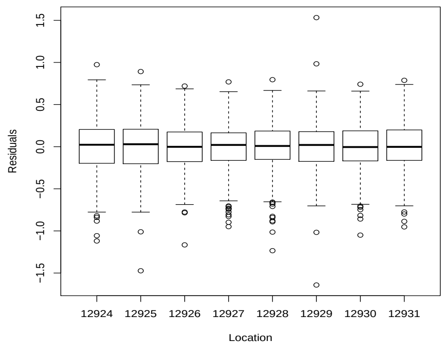
Table 3: Ordering of the models for AIC and BIC, Model_A and Model_B, respectively, using the measures Δ_{Ai} and Δ_{Bi} and the associated relative likelihoods w_{Ai} and w_{Bi} derived from (1). Model identifiers are given in Table 2. Relative likelihoods are given to three decimal places and those given as 0 denote values less than 0.001.

Model_A	Δ_{Ai}	w_{Ai}	Model_B	Δ_{Bi}	w_{Bi}
2	–	0.665	5	–	1.000
1	1.994	0.245	2	33.593	0
5	4.019	0.089	1	41.857	0
6	250.165	0	8	241.902	0
8	252.190	0	6	283.759	0
4	1514.174	0	7	1505.911	0
7	1516.198	0	4	1547.778	0
9	1631.253	0	9	1658.578	0
3	1710.309	0	3	1737.634	0

Based on this analysis, our preferred model is Model 5 which includes terms for analysts and machines, accounting for random variation amongst the sixteen samples and the two ends of the notes, nested within the samples. This model does not include a term for location. A visual confirmation of this lack of differences amongst locations is presented in Figure 1. This plot shows boxplots of the residuals of Model 5, split by location. The residuals of this model are the part left over in the data after account is taken of the differences between analysts and machines, accounting for variation amongst samples and ends of notes within samples. The solid lines in the boxes are the median values of the

residuals, the ends of the boxes are the quartiles and the open circles are outliers, observations outside 1.5 times the interquartile range of the data. There is very little difference in these boxplots. In particular, the medians are almost identical. If there were a difference in the quantities of cocaine on banknotes amongst locations then this would show as differences in these boxplots (i.e. the summary statistics would vary with location). As is illustrated in Figure 1 there is no such variation.

Figure 1: Boxplots of residuals for each of the eight locations from which banknotes were provided. The residuals are those from the linear mixed effects Model 5 with analyst and machine as fixed effects and accounting for variation amongst the sixteen samples treated as random effects and between the two ends of the banknotes treated as random effects.



Scatter plots of the residuals *versus* the fitted values for models 1 and 5 are shown in Figure 2. For a well-fitting model, it would be expected that this plot would be approximately symmetric about the horizontal line through zero, with no obvious change in the size of the residuals at different fitted values. There is no strong evidence that this is not the case. For fitted values below 15, it could be perhaps be argued that the residuals are smaller than for larger fitted values, but this only affects a small proportion of the observations and so will not have a large effect on the results. It can also be seen that there is very little difference between the plot for Model 1 (with location as a covariate) and the plot for Model 5 (without location as a covariate). This means that adding location as a covariate makes little impact on the residuals of Model 5 and so is further evidence to suggest that there is little variation by location in the quantities of cocaine on banknotes in general circulation throughout England and Wales.

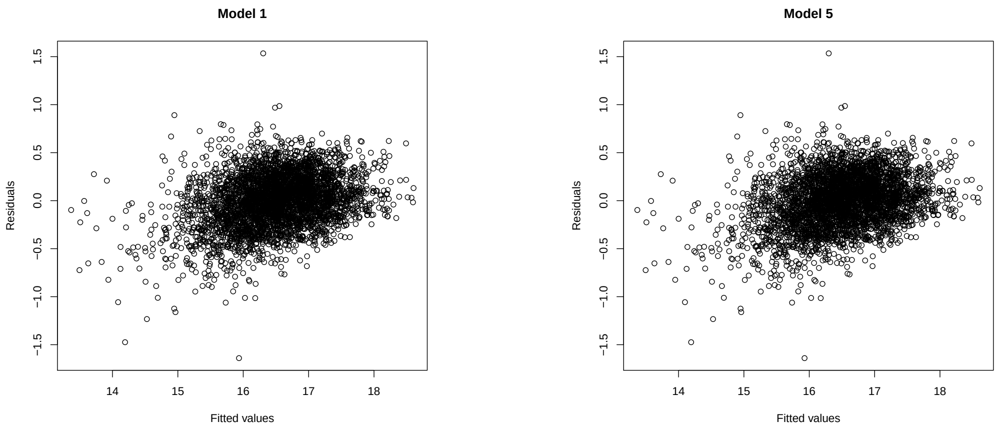


Figure 2: Scatter plots of residuals against fitted values for models 1 (Left; Location, Analyst, Machine, Sample, Note) and 5 (Right; Analyst, Machine, Sample, Note)

Inference from model 5

Model 5 is a model in which the log peak area of the measurement of the quantity of cocaine on a banknote is

linearly related to fixed effect terms for Analyst and Machine and random effect terms for Sample and Note. The expected values for the random effects are zero. Thus, the expected response of log peak area has three terms, an intercept term corresponding to a mean effect for Machine C and Analyst 1 and two fixed effect terms for machine and analyst which provide additive components to the model for Machine F and Analyst 2. The results are given in Table 4.

Table 4: Expected value of log peak area of quantity of cocaine on a banknote for four combinations of Machine (C or F) and Analyst (1 or 2) for Model 5

Machine	Analyst	Expected log peak area
C	1	16.12
C	2	16.68
F	1	16.31
F	2	16.87

5. Discussion

Nine models were considered as listed in Table 2. Inspection of the AIC and BIC values and differences from the minima of the two measures as given in Table 3 show the models may be put into three groups. Group A consists of models 1,2 and 5 with the smallest AIC and BIC values and smallest differences from the minima. Group B consists of models 6 and 8 with medium AIC and BIC values and medium differences from the minima. Group C consists of models 3, 4, 7 and 9 with large AIC and BIC values and large differences from the minima. A good discussion of the meaning of words such as 'small', 'medium' and 'large' in this context is given in [4].

> 'The larger the Δ_i, the less plausible is fitted model i as being the best approximating model in the candidate set. . . . Some simple rules of thumb are often useful in assessing the relative merits of models in the set. Models having $\Delta_i \leq 2$ have substantial support (evidence), those in which $4 \leq \Delta_i \leq 7$ have considerably less support, and models having Δ_i have essentially no support.' [4]

Model 2 differs from model 1 in that 'Sample' is dropped in model 2 and included in model 1. This suggests that the sample to which the note belongs has little effect on the quantity of cocaine on the banknote. Exclusion of *Location* in the comparison of model 1 with model 5 also has little effect on the quality of fit and indicates that the origin of the banknote has little effect on the quantity of cocaine on the banknote. This result supports the result from [6] and shows that the finding of no variation with location still holds in 2015.

Removal of *Note* from model 2 to give model 3 leads to a large drop in the quality of fit and suggests that there is variation in the quantities of cocaine on individual banknotes. Comparisons of models 1 and 4, and of models 5 and 7 show that there is a big effect owing to *Analyst* as removal of *Analyst* from the model to be fitted leads in both cases to a large increase in AIC and BIC. Removal of *Machine* in comparing model 5 with model 8 shows that *Machine* has a moderate effect. Removal of *Location* in comparing model 6 with model 8 leads to a small *decrease* in AIC and a very small *increase* in BIC. These results are consistent with the proposition that *Location* has no effect on the quantity of cocaine on banknotes in general circulation. The omission of both *Analyst* and *Machine* to give model 9 has a big effect on AIC and BIC indicating that both these factors should be retained.

The inclusion of the location of a banknote as a factor in the model makes little difference to the goodness-of-fit. No meaningful support was found for the proposition that there is regional variation in the quantities of cocaine in banknotes in general circulation in England and Wales. If location were associated with the quantity of cocaine then there would be a large increase or reduction in the values of AIC and BIC following its omission or inclusion, respectively. A comparison of models 1 and 5 shows that the omission of *Location* makes little difference to the goodness of the fit and thus that the general location from which a banknote in general circulation is sourced is not associated with the quantity of cocaine on it.

It is always possible to argue that more is better. However, the data collected and analysed by MSA since those reported on in [6] and the results in this paper provide evidence that a suggestion to tailor the background database for a particular case may not be important. The current database of banknotes used to represent banknotes in general circulation has been confirmed by this study as fit for purpose. Also note that, whilst it may be true, as noted in *R. v. Rashid and others* (p.31), that the *quantities* of cocaine on banknotes have increased in the time (March 2004) since the study reported on in [6] was conducted, this current study provides no evidence to suggest the *variation* in quantities of cocaine has changed.

6. Acknowledgement

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