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The when and where of an emerging crime type: The example of metal theft from the railway network of Great Britain

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Abstract Metal theft has become an increasingly common crime in recent years, but lack of data has limited research into it. The present study used police-recorded crime data to study the spatial and temporal concentration of metal theft from the railway network of Great Britain. Metal theft was found to exhibit only weak seasonality, to be concentrated at night and to cluster in a few locations close to – but not in – major cities. Repeat-victimisation risk continued for longer than has been found for other crime types. These and other features appear to point to metal theft being a planned, rather than opportunistic, offence and to the role of scrap-metal dealers as facilitators.
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Introduction

Over the past 5 years, the problem of the theft of metal from infrastructure networks, heritage sites and homes has become a major concern for policymakers in several countries. The United Kingdom (UK) Home Office (2013) defined metal theft as 'thefts of items for the value of their constituent metals, rather than the acquisition of the item'. The impact of such thefts reported by Brathwaite *et al* (2013, p. 6) appears to be typical of many areas:

> citizens have experienced disruptions to rail services, interruptions to telecommunications, theft of lead and copper from the roofs of churches, schools, private and council buildings, the theft of street signs, gully and manhole covers, and, most reprehensible, theft from war and grave memorials.

Thefts of metal from transport and telecommunications networks are particularly noteworthy because the act of removing metal often causes those networks to fail, causing disruption across a wide area.

Metal theft is not a new phenomenon, with historical accounts in both the UK and United States stretching back to the seventeenth century (Bennett, 2008; Posick *et al*, 2012).

Nevertheless, until recently thefts appear mostly to have been infrequent enough to be regarded as a tolerable nuisance rather than a substantial threat. In recent years the attitude of victims has changed, most likely because the number of reported incidents has increased substantially.

Weisburd *et al* (2009) charted the increasing geographic specificity of the study of spatial crime variations, from nineteenth and early-twentieth century studies of differences between regions, through mid-twentieth century neighbourhood-level studies to modern research on street segments and point locations. As an emerging crime problem, the study of metal theft is only at the start of this spectrum, with most studies focusing on regional variation. Indeed, there have so far been few studies of metal theft of any type: the present authors were able to find only four empirical articles (Whiteacre and Howes, 2009; Sidebottom *et al*, 2011; Posick *et al*, 2012; Sidebottom *et al*, 2014) on the subject, together with a small number of reports from government and other organisations.

Using a survey methodology, the American Association of State Highway and Transportation Officials (2013) found that metal thefts from highway infrastructure were concentrated in a few US states, but did not consider any intra-state variation. Whiteacre and Howes (2009) studied the incidence of metal theft in 51 cities in the United States. They noted that thefts clustered in certain cities and found a positive relationship between the number of scrap-metal dealers (SMDs) in a city and the number of reported metal thefts. In the UK, government research (Home Office, 2013) has found that metal theft was concentrated in a few police-force areas.

The only published study of which the present authors are aware that considered intra-regional variation of metal theft is Posick *et al* (2012). They found that commercial and residential burglaries in Rochester, NY, in which metal was stolen were clustered in certain areas of the city, but were less clustered than burglaries in which metal was not stolen.

The purpose of the present study was to identify patterns of spatial and temporal concentration of thefts of metal from the railway network in Great Britain. Particular emphasis was placed on identifying the ways in which such patterns were consistent or inconsistent with those for other types of theft. Railway-metal theft was chosen both because of the disruption it causes and because British Transport Police (BTP), the specialist police force covering railways in Britain, began to consistently record metal thefts before most other police agencies did so. The difficulty in obtaining data on metal theft means that, to the authors' knowledge, the present study uses the largest metal-theft data set yet assembled. As data were available for every recorded incident of metal theft in Great Britain over a 6-year period, the present study was able to consider intra-regional variation to a degree not previously possible.

There are likely to be both theoretical and practical benefits to studying the spatial and temporal distribution of an emerging crime type. Most research on theft has concentrated on the types of theft most commonly experienced in developed countries, for example, theft of and from vehicles, burglary, robbery and shoplifting. From these studies have come a number of rules-of-thumb on the concentration of theft (and indeed high-volume crime more generally), for example, the 'iron law of troublesome places' (Wilcox and Eck, 2011, p. 476) discussed below. These rules can usefully be tested on a new type of theft not previously studied in detail to determine whether they still apply. As well as being useful for the academic community, the increasing popularity of evidence-based policing (Sherman, 1998; Lum and Koper, 2014) means these same rules are now being used by practitioners to inform their decisions.

In addition to being an emerging crime type, live-metal theft as studied in this research has two particular features of interest. The first is that there is an established link between theft of metal and its market value (for example, Sidebottom *et al*, 2014). This implies that financial motivation is a contributing factor, and therefore that restricting access to the market could have some preventative implications (Sutton, 2014). The second is that there are, in comparative terms for theft, often (but not always) higher risks involved in carrying out this offence, because of the possibility of exposure to electric current (Taylor *et al*, 2003). This, along with other factors such as restricted access to live metal, might have implications in terms of the method by which the offence is carried out, and we explore this possibility in the analysis which follows by searching for signatures that could imply forward planning by offenders.

Railway-Metal Theft

Great Britain has the second-most intensively used railway network in Europe (Eurostat, 2011), with 6.98 million railway services carrying passengers on 1.35 billion journeys each year (Office of Rail Regulation, 2012). This intensive service means that any disruption to the network quickly causes delays to passengers and freight services.

When considering metal thefts from railways, a distinction can be made between thefts of metal that is *in use as part of the network*, such as signalling cable and telecommunication wire (known as ‘live’ metal), and thefts of other metal, such as lead from the roof of a station or palladium contained in catalytic converters stolen from cars in station car parks. The classification of live metal does not necessarily require the metal to be carrying electric current at all times; the only consideration is whether the metal forms part of the systems necessary for safely running trains. Live-metal thefts are commonly more disruptive because the metal involved is often essential to the operation of train services.

Figure 1 shows different types of metal typically found on railway lines. All of these metals can be stolen, but copper signalling and telecommunications cable is perhaps the most vulnerable because it is relatively easy to cut and carry away. By contrast, those attempting to steal power cables risk death or disfigurement from electrical burns (Taylor *et al*, 2003; Gorse *et al*, 2013). Sidebottom *et al* (2014) found that most railway-metal thefts involved the theft of copper cable.

Data

One of the reasons that there are few studies of metal theft is the difficulty in obtaining data. Outside those agencies that record metal theft as a specific crime type, incidents may be recorded under several different headings. For example, theft of a catalytic converter from a car on the street would be recorded as a theft from a motor vehicle, whereas theft of a drum holding copper wire from a warehouse would be recorded as a non-residential burglary.

The present study was based on reports of 5044 thefts of live metal between January 2007 and December 2012, provided by BTP. The study concentrated on live-metal theft because of the disruption it causes, and also because live-metal theft is a relatively homogeneous crime type. Clarke (1983, p. 232) argued for the importance of analysing ‘highly specific’

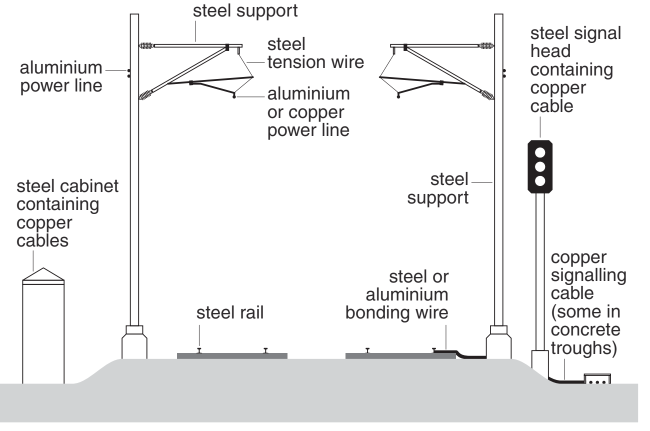

Figure 1: Metal vulnerable to theft on a typical railway line.
Source: Goldring and Suddards (1971) and Glover (2013).

types of crime so as to be able to understand their specific characteristics. Non-live-metal theft is a much more heterogeneous category.

Police-recorded crime data were used because – although not all crimes are reported to police – such records are the only source of local information on metal theft. Alternative sources of data, such as surveys of victims or offenders, used for other types of crime are not available for metal theft. Carrying out such surveys would also be unlikely to be cost effective since, because live-metal theft causes substantial disruption to railway services, service providers are likely to be highly motivated to report it to the police.

In 2 per cent of cases, there was insufficient information in the crime report to enable the crime to be geocoded to any location on the railway network. The resulting geocoding 'hit rate' of 98 per cent is much higher than the minimum rate of 85 per cent that Ratcliffe (2004) found was necessary in order to assume that the uncoded offences would not change the apparent distribution of crimes. However, Ratcliffe (2005, p. 110) noted that the 85 per cent threshold applies only if uncoded offences are believed to be randomly distributed. In the present study this assumption could not be made, because in some cases several crime reports gave the same uncodable offence location. Nevertheless a hit rate of 98 per cent is higher than is commonly achieved by police crime analysts (Ratcliffe, 2010a, p. 9) and is similar to or higher than found elsewhere in the literature (see, for example, Andresen, 2006, p. 266; Groff *et al*, 2010, p. 13; Ratcliffe *et al*, 2011, p. 808).

The main limitation on the data used in this study was the degree of uncertainty about the locations of offences. Metal thefts often occur at remote locations by the side of railway tracks, some distance from the nearest road or postal address. As these features are often used for geocoding of crime, identifying the precise locations of railway-metal thefts can be difficult. For this reason, BTP commonly records line-side crimes as happening at the nearest of the 2527 passenger stations on the network. In the case of live-metal theft, 84 per cent of offences were coded as happening at stations, even though fewer than 1 per cent of offences happened within the confines of a station.

In order to reflect this spatial uncertainty in the present analysis, those few thefts that were not already recorded as occurring at stations were counted as happening at the nearest station. Since the nearest station in Euclidean space to a particular offence may be on a different railway line to the offence location, it was necessary to take into account the structure of the railway network during this matching procedure. This was done by calculating a Voronoi polyline for each station, where the polyline for each station included all the railway track that was closer (by network distance) to that station than to any other. The median Voronoi polyline was 3.9 km in length, with an interquartile range of 5.1 km. For the remainder of this study, references to offences at railway stations should therefore be read as offences occurring at a particular station *or* nearer to it than to any other station.

In order to allow comparison of metal theft with other types of theft from the railway network, data on all thefts from the railway network were obtained from the publicly available www.police.uk service provided by the Home Office. This service provides coordinates for all recorded crimes in England and Wales. Since May 2013, these records have been broken down into 13 offence types. Between May and October 2013, there were 25 400 theft offences on the railway network, which were recorded as either robberies and personal thefts (24 per cent of offences), thefts of bicycles (23 per cent), thefts from shops (8 per cent), thefts of and from motor vehicles (6 per cent), burglaries (1 per cent) or miscellaneous other thefts (38 per cent).

In order to protect the anonymity of victims of crime, the Home Office does not release the precise coordinates at which offences occurred. Instead, before records are released their locations are changed to those of the nearest ‘snap point’, which is typically the centroid of the street on which the offence occurred. However, for offences at non-residential locations such as railway stations, no snapping takes place and actual locations are given (Ray *et al*, 2012). As such, it was possible to allocate all theft records to a station Voronoi polyline.

Except where noted, spatial analysis was conducted in ArcGIS 10.1 (ESRI, 2012). Non-spatial analysis was conducted in R (R Core Team, 2013), with the ‘circular’ package (Agostinelli and Lund, 2011) used for calculating circular statistics.

Long-Term Patterns of Live-Metal Theft

Figure 2 shows the frequency of live-metal thefts from the railway network between 2007 and 2012, overlaid with the international wholesale price of copper on the London Metal Exchange during that period. The number of thefts each month appears to be volatile, with between 20 and 131 offences occurring. There have been two peaks in metal theft, extending from early 2007 to late 2008 and then from early 2010 to late 2011. These peaks were each followed by sharp decreases in the frequency of thefts, such that by the end of 2012 there were fewer offences than at any time in the previous 6 years. Sidebottom *et al* (2011) discussed the close correlation between the incidence of theft and the price of copper, concluding that thefts are at least partly driven by the changing value of copper. Figure 2 shows that this relationship appears to have broken down during 2012, when the price of copper remained steady but the number of thefts dropped sharply. This may be due to the introduction of a factor not previously present, such as increased targeted policing or better physical security (see Sidebottom *et al*, 2014, for further discussion).

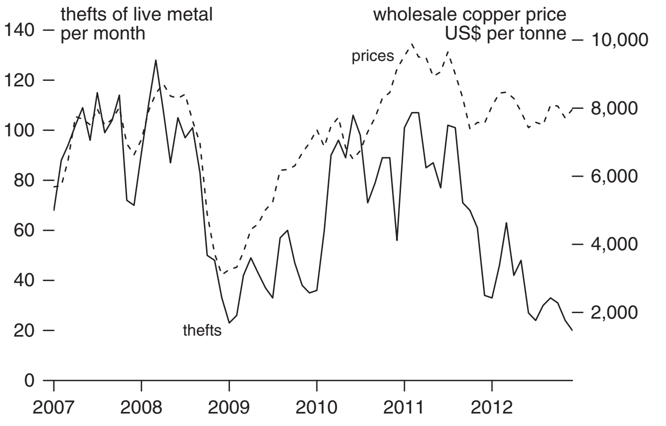

Figure 2: Long-term variation in theft of live metal from the British railway network (2007–2012).
Source: Copper price data from World Bank (2013).

Figure 3 shows the occurrence of live-metal theft throughout the years 2007–2012. Many types of theft, such as burglary (Hird and Ruparel, 2007), thefts of and from motor vehicles (Andresen and Malleson, 2013) and street robbery (recently reviewed by Tompson and Bowers, 2013), exhibit strong seasonal variation. A review by Baumer and Wright (1996) found that the frequency of many types of theft increases in the summer and decreases in the winter, although this is not universal – Yan (2004) found no evidence of seasonality in residential burglary in Hong Kong.

Temporal crime patterns are usually represented as if they are linear, but Felson and Poulsen (2003, p. 597) demonstrated that doing so can obscure important systematic variation. Brunsdon and Corcoran (2006) recommended using circular statistics to overcome this problem, a recommendation followed here. The Rayleigh test of circular uniformity (Jammalamadaka and SenGupta, 2001, p. 132) can be used to determine whether events are uniformly distributed throughout a cyclical period of time. This test showed that thefts do not occur uniformly throughout each year ($\bar{r} = -0.145$, $P<0.001$). However, the Rayleigh test does not give any indication of the degree of non-uniformity over the year. Visual assessment of the histogram sectors and density curve (particularly in comparison with the median density) in Figure 3 suggests that the volume of thefts is similar from February to October (with a slight peak in March) and lower between November and January. The degree of seasonal variation appears to be less than that found for other crimes by, for example, Hird and Ruparel (2007, pp. 5–6).

The most obvious seasonal trend evident in Figure 3 is the sharp decrease in crimes in the final 2 weeks of each year, when there were an average of 13 crimes each year compared with 32 crimes per fortnight during the rest of the year. Although completed research is limited, there is a widespread belief that much stolen metal is sold to SMDs. As many SMDs do not trade between Christmas Eve and New Year's Day, thieves will not be able to sell stolen metal during that period. Previous research shows that shoplifters and burglars commonly dispose of goods within hours (Stevenson, 2001, p. 112) or even minutes (Sutton, 2008, p. 41) of stealing them. Rapid disposal of stolen goods both ensures that thieves benefit

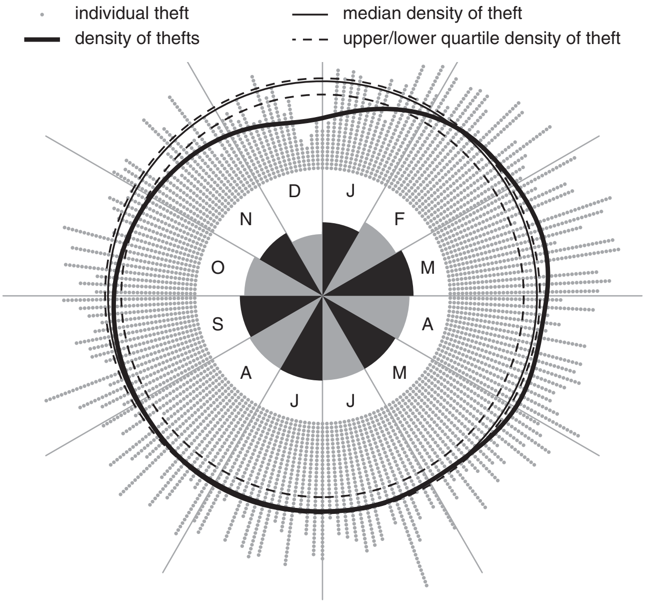

Figure 3: Variation in theft of live metal from the British railway network throughout the year (2007–2012).
Notes: Dots on the outer circle show individual crimes, with a black line showing the density of offences with bandwidth calculated to minimise error as determined by Hall *et al* (1987, p. 758). The area of each histogram sector shows the number of offences during each month of the year.

from the proceeds and minimises the risks of being caught with the goods, but it is not clear which of these factors (if either) plays a greater role in motivating metal thieves.

Short-Term Patterns of Live-Metal Theft

Between 2007 and 2012 there were a mean of 2.3 live-metal thefts each week from the British railway network. Thefts occurred with approximately equal frequency on all days of the week except Sundays, when there were 30 per cent fewer offences.

In common with many other types of theft (see Ashby and Bowers, 2012, for a review), many police records of metal theft do not include the exact time at which the offence occurred. Instead, they specify a range of times between which the crime occurred. For the 38 per cent of crimes with an apparent duration of over 4 hours, aoristic analysis (Ratcliffe and McCullagh, 1998) was used to estimate the most likely offence times. Aoristic analysis allocates fractions of crime counts to each period in which a particular crime could have occurred. The resulting aoristic value for each period can be interpreted as the estimated number of crimes that occurred during that period. Figure 4 shows that live-metal theft is a night-time crime: there is a peak overnight on every day except Sunday night/Monday morning, such that 46 per cent of offences occurred between 23:00 and 07:00 hours.

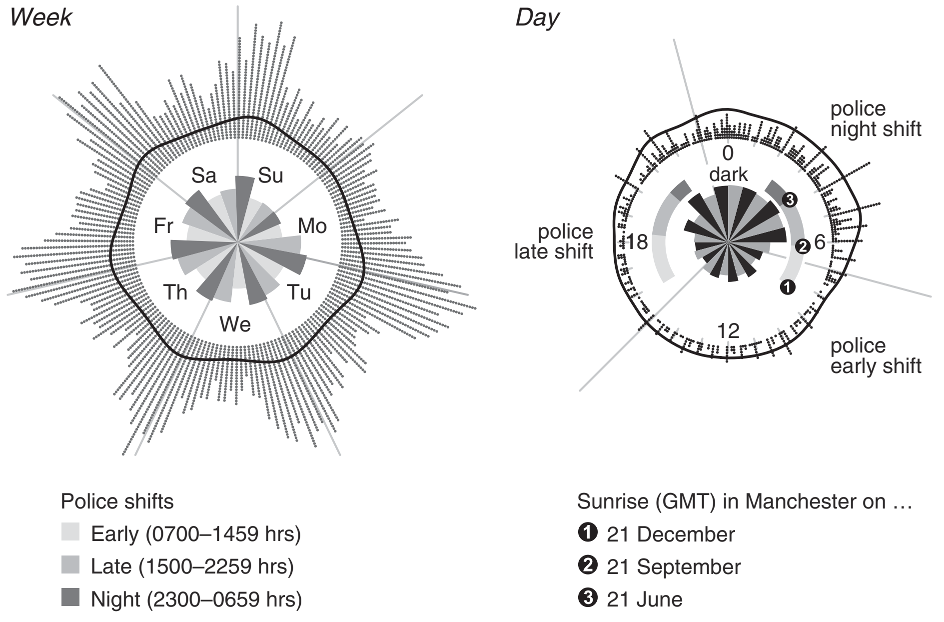

Figure 4: Variation in theft of live metal from the British railway network throughout the week and day (2007–2012).
Notes: Dots outside the circular axis show offence times, black lines show the density of offences over time. The area of each sector in the central histogram shows the number of offences during each police shift (left) and hour (right). Offence times during the week (left) were determined aoristically (see text), whereas times during each day (right) are only shown for offences occurring in 4 hours or fewer.

The second panel of Figure 4 shows the daily pattern of offences. It was not possible to use aoristic analysis at this scale, because when crimes have a long duration it is common for police to record the range of potential offence times only to the nearest hour. As such and following the recommendation of Ratcliffe (2002, p. 33), only offences with a duration of 4 hours or less were included. The peak offending times are between 21:00 hours and 06:00 hours, with the fewest offences occurring during the morning and evening commuting hours.

The relative frequency of metal thefts at night corresponds with a similar night-time peak in commercial burglaries found by Hakim and Shachmurove (1996, p. 450). Imprisoned burglars interviewed by Butler (1994) emphasised the importance they placed on offending at times and places where the chance of being stopped by police was minimal. The same rationale may explain the night-time peak in metal thefts. The frequency of train services on many lines is likely to make stealing live metal very difficult during peak hours. In contrast, there are fewer trains in the late evening when thefts are more common. Although there are very few passenger trains between 01:00 and 05:00 hours, the absence of trains cannot wholly explain the overnight peak in offending. The true explanation may be the combined effect of the relative infrequency of trains after 21:00 hours and the decreased risk of being observed during the hours of darkness.

Repeat Thefts

Repeat victimisations, which in the context of railway-metal thefts means repeated offences at the same location, have been recognised in the literature at least since Farrell and Pease (1993) found that repeat offences at a small number of locations or against the same victims accounted for a substantial proportion of all offences. Townsley *et al* (2000) found that once a crime had occurred at a particular location, surrounding locations also had an increased risk of victimisation, at least temporarily (see Johnson, 2010, for a review), known as 'near-repeat' victimisation. In the present research, the aggregation of theft locations to the nearest station meant that it was not possible to differentiate repeat from near-repeat offences. In the following discussion, the term 'repeat' should be taken to cover both repeat and near-repeat offences, which were analysed together.

Johnson *et al* (2007) used Knox ratios (Knox, 1964) to quantify the difference between the number of offences observed at previously victimised locations relative to the expected number if being victimised once was associated with no additional risk of being victimised in future. Knox ratios can also be expressed as percentage changes in risk, where a ratio of 2 is equivalent to a 100 per cent increase in risk compared with that expected if there was no repeat victimisation.

The period of which repeat-victimisation risk persists appears to vary by crime type. Johnson *et al* (2007), studying repeat residential burglaries in five different countries, found that locations were at additional risk of victimisation for 2 weeks after a first burglary occurred there. A further study of residential burglary in two areas of the UK by Johnson *et al* (2009) found an at-risk period of 6 weeks, as well as a period of 2 weeks for thefts from motor vehicles. Youstin *et al* (2011) found that repeat-victimisation risk persisted for 8 weeks for shootings, thefts of motor vehicles and street robberies in Jacksonville, Florida, although they do not state whether they tested for risk beyond this period. Also studying shootings, this time in Philadelphia, Ratcliffe and Rengert (2008) found an elevated risk for 2 weeks after an initial offence.

The near-repeat calculator (Ratcliffe, 2009) was used to calculate Knox ratios, along with *P* values determined using a Monte Carlo simulation with 1000 iterations. This procedure compares the counts of crimes over different periods, and therefore requires the selection of a suitable temporal bandwidth. The near-repeat calculator can deal with a maximum of 30 temporal bands in one run, so to maximise the information returned the software was run with bandwidths from 1 to 7 days, after which the most-detailed data were used for each time period.

Figure 5 shows the ratios produced by the near-repeat calculator, along with a non-parametric locally weighted scatterplot smoothing (LOESS) curve (Cleveland *et al*, 1992). The LOESS smoothing algorithm, which is analogous to other smoothing methods such as kernel-density estimation (Levine, 2013, 10.1), fits a local regression model to each part of the distribution, with the proportion included in each part represented by the parameter λ.

Following a live-metal theft at a particular location, a significant additional risk of a further offence occurring at the same location was found for 3 months afterwards. The additional risk fell over time, so that half of the additional risk had dissipated within 3 weeks. Despite this reduction, repeat-victimisation risk then continued to be significantly greater than would be expected under the null hypothesis until at least 12 weeks after the initial offence. This is substantially longer than has been found in any other study of which the authors are aware.

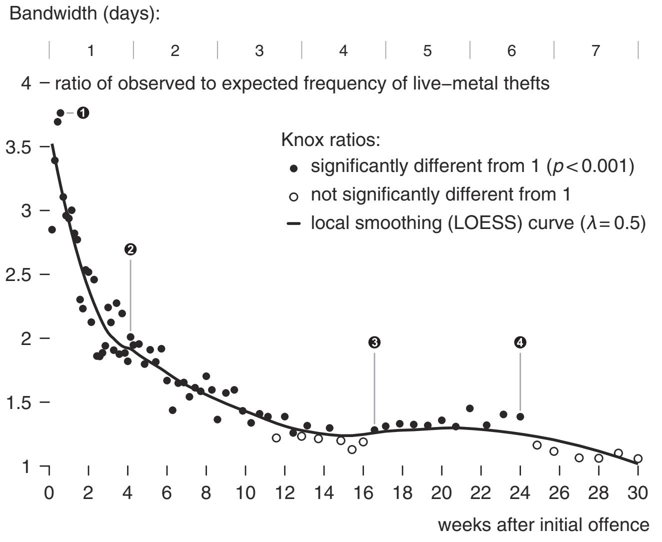

Figure 5: Repeat-victimisation risk in live-metal theft from the British railway network over time (2007–2012). *Notes*: Four days after the initial offence (1), repeat offences at the same location are 3.8 times more likely than would be expected by chance. After 4 weeks (2), repeat offences are twice as likely as would be expected by chance. A second, less intense, period of increased risk appears to start after 4 months (3) and continue until five-and-a-half months after the initial offence (4).

Johnson (2008, p. 219), reviewing studies of repeat burglary from several countries, found that repeat-victimisation risk usually decays over time approximately according to an exponential function, with the greatest risk immediately after the initial offence. By contrast, the greatest repeat-victimisation risk of metal theft appears to be present 4 days after the initial offence rather than immediately afterwards. However, this maximum Knox ratio does not appear to be further from the smoothing line than several other points within the distribution, so it is difficult to come to any clear conclusions about the importance of this finding.

Unexpectedly, a second period of significant additional risk was found between 17 and 24 weeks after the initial offence. This could be a statistical artefact, created by a ‘long tail’ of marginally significant ratios, some above the critical value of P and some below. However, it could also suggest that offenders are more likely to return to an area after a certain period, perhaps because they believe that focused police patrols will have stopped or that the stolen metal will have been replaced. Without detailed information on patrol patterns or replacement schedules, it was not possible to test either of these hypotheses.

The presence of repeat-victimisation risk is important for policymakers because one common police response to a crime occurring is to increase patrols in the same area immediately afterwards. In the case of railway-metal theft, it appears that such tactics are likely to have merit. Since the greatest risk of repeat victimisation is found in the first week after an initial offence, it appears that hotspot policing is likely to be most effective if put in place quickly.

Spatial Concentration of Live-Metal Theft

Braga (2013) argued that it has become axiomatic in the study of crime that offences are unevenly distributed in space. Spatial concentration of theft offences has been found in relation to residential burglary (Shannon, 1954; Brantingham and Brantingham, 1975; Brown, 1982), street robbery (Sherman *et al*, 1989; Smith *et al*, 2000; Ceccato and Oberwittler, 2008), thefts from shops (Nelson *et al*, 1996; Fitzgerald *et al*, 2004; Cheng and Williams, 2012) and theft of motor vehicles (Barclay *et al*, 1996; Rengert, 1997; Chainey *et al*, 2008).

In the present study, metal thefts were found to be strongly concentrated at a few locations: half of all metal thefts occurred at 3 per cent of railway stations, whereas there were no metal thefts at 63 per cent of stations. A similar concentration of crime has been found in other settings (for a review, see Weisburd *et al*, 2004, pp. 287–288), with a similarly disproportionate amount of crime occurring at a few 'risky facilities' (Eck *et al*, 2007). Figure 6 shows a Lorenz curve (Lorenz, 1905) comparing live-metal thefts from the railway network with all other thefts from that network. The similarity between the two curves is confirmed by the similar Gini coefficients of 0.87 for live-metal theft and 0.86 for all railway thefts. Metal theft therefore appears to follow the 'iron law of troublesome places' (Wilcox and Eck, 2011, p. 476): a few places experience most offences, some experience the remaining offences and the majority of places experience no offences at all.

Figure 7 is a choropleth map showing the number of live-metal thefts per year per 10 km of track within the Voronoi polyline for each station. Choropleth maps have been largely replaced in the academic study of crime (see Chainey *et al*, 2008, for a comparison of alternatives), but they may be the least-worst alternative when data are only available as counts of offences in areal units. Choropleth maps are problematic for two inter-related

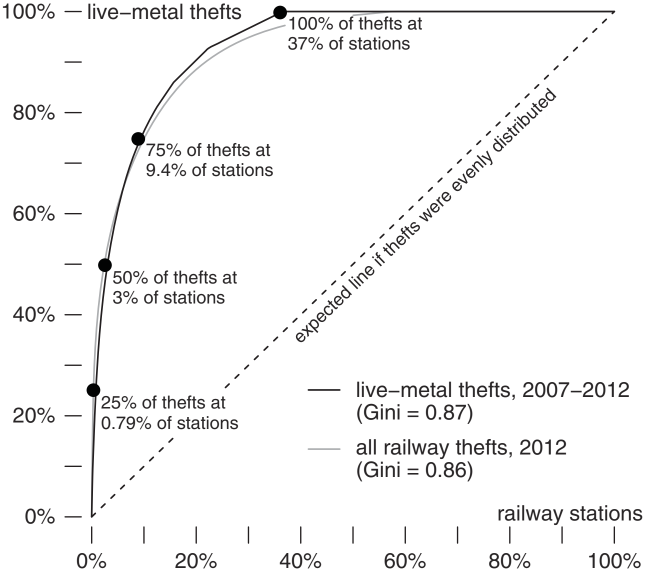

Figure 6: Spatial concentration of live-metal theft from the British railway network (2007–2012).
Source: Details of all railway thefts obtained from data.police.uk/ for the calendar year 2012.

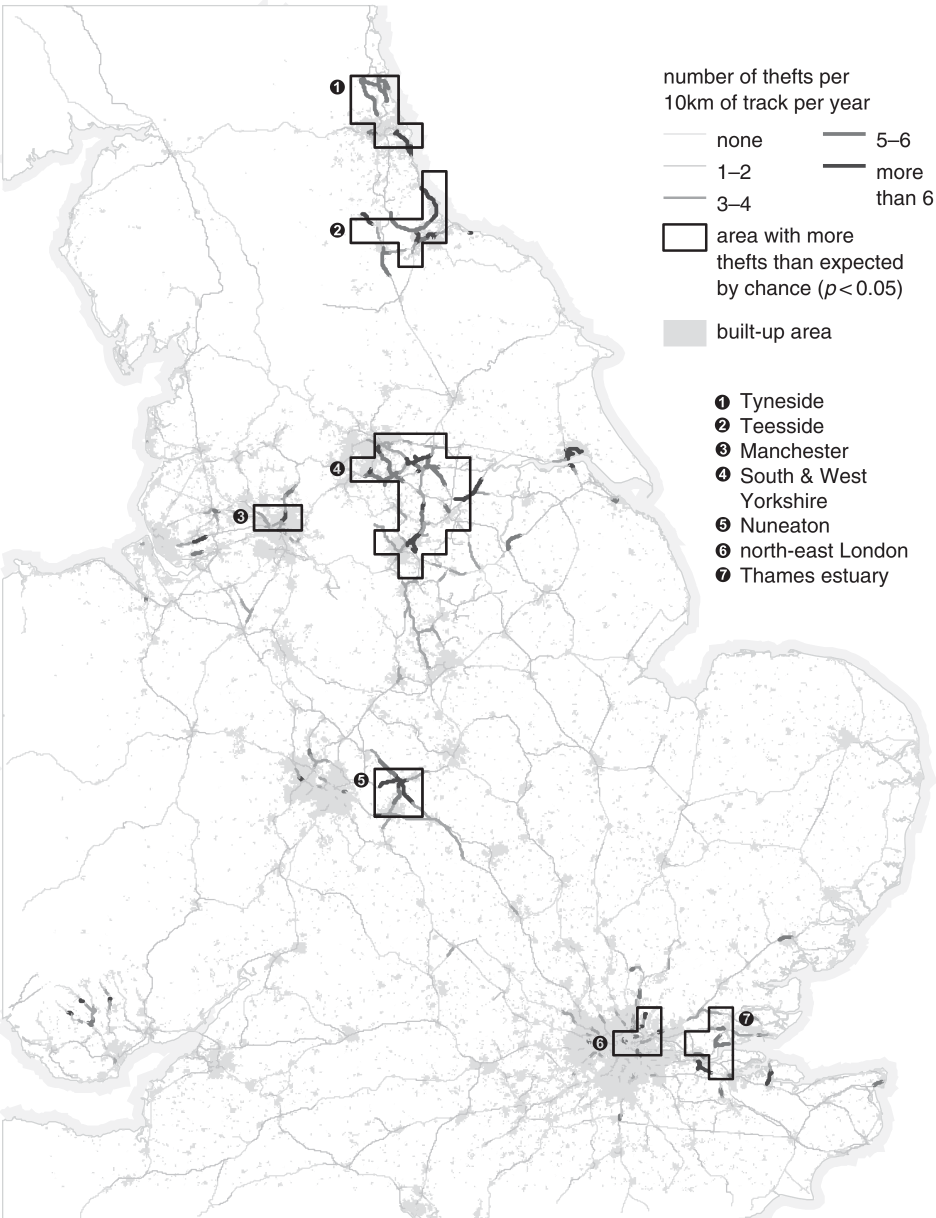

Figure 7: Map of live-metal theft from the British railway network (2007–2012).
Notes: Hotspots were determined by calculating the G_i^* statistic (Getis and Ord, 1992).
Source: Office for National Statistics and Ordnance Survey.

reasons. The first is that they do not show the precise locations of offences, but (as discussed above) this is an inevitable limitation of the present data and will not be considered further. The second is the modifiable areal unit problem (MAUP), description of which is usually credited to Openshaw and Taylor (1979) but dates at least to Yule and Kendall (1950, p. 313). This describes how the results of spatial analyses can be strongly influenced by the choice of both study area and spatial units of analysis within that area, particularly when the chosen area and units are arbitrary. In the present research, the study area was neither arbitrary nor modifiable, as it covers the entire railway network. The choice of the Voronoi polyline as the unit of analysis was modifiable, since another unit could have been chosen. Weisburd *et al* (2012, p. 23) argued that researchers should use the smallest spatial unit of analysis compatible with the precision of the underlying data. The Voronoi polyline was chosen with this axiom in mind, as the previously described data limitations mean no smaller unit could be used[1].

Three observations are apparent from Figure 7: offences are clustered in a few hotspot locations, those hotspots are themselves clustered close to one another and hotspots tend to occur close to, but away from the centre of, cities.

It appears that there are large parts of the railway network in which metal theft is not a substantial problem. The significance of spatial clustering can be determined by comparing (using notation from Chainey and Ratcliffe, 2005) the mean observed distance ($\overline{d}$) between each crime and the nearest crime to it with the expected mean distance ($\overline{\delta}$) if crimes were distributed with complete spatial randomness (CSR). Expressed as a ratio $\overline{d}/\overline{\delta}$, this is known as the nearest neighbour index (NNI).

Calculating the NNI is straight-forward for offences that occur in Euclidean space, but more complicated for those occurring on a network. As metal thefts can only occur on railway lines, it was necessary to calculate $\overline{\delta}$ by determining the mean distance between 5044 points placed at random intervals along the railway network. Similarly, as many metal thefts were recorded as occurring at the nearest railway station to the place at which they actually occurred, $\overline{d}$ was determined by placing points at random intervals within the Voronoi polyline associated with each station. As such, the calculated NNI represents a conservative estimate of the degree of spatial clustering, as it is likely that crimes were clustered within each station polyline. As both were based on random distributions of points, $\overline{d}$ and $\overline{\delta}$ were each calculated 10 times and their mean values used to calculate an NNI of 0.65[2]. Following the procedure described by Clark and Evans (1954), a z-score of 12.98 was calculated, confirming that metal thefts were significantly more clustered than would be expected by chance. Although this result accords with findings in a great many other studies of crime, it is important for practitioners to remember that even an 'epidemic' of metal theft (Milmo, 2008; Hough and Millward, 2011; Wright, 2011) can be restricted to a few parts of the country. This observation suggests that nationwide interventions may be less efficient than local problem-solving in hotspot areas.

The second observation from Figure 7 is the apparent clustering of hotspots close to one another, particularly in the middle of the UK. Such spatial autocorrelation has been previously observed for residential burglary (Bernasco and Luykx, 2003), street robbery (Bernasco and Block, 2011) and vehicle theft (Andresen, 2006). A Moran's I test (Moran, 1950) can be used to determine whether observed spatial clustering of hotspots is significantly greater than would be expected under a null hypothesis that hotspots were distributed with CSR. $I=1$ indicates complete correlation, $I=0$ indicates CSR and $I=-1$ indicates complete dispersion. The test requires aggregation of the study area into a grid. Following the procedure used by Marchione and Johnson (2013), Great Britain was divided into 10-km squares, those squares through which no railway lines passed were removed and the number of metal thefts falling within each grid square was counted. As for the NNI test, this procedure was repeated 10 times with crimes randomly positioned within each station Voronoi polyline. As the I test compares the number of thefts in each cell with those in neighbouring cells, the user is required to specify which cells should be treated as neighbouring the cell being tested. In this case, following Ratcliffe (2010b, p. 25), cells were treated as neighbouring one another if their outlines touched at any point. The mean result of this procedure was $I=0.61$ ($P<0.001$). As this value was positive, the observed hotspots were more clustered than would be expected under CSR and so hotspots were themselves clustered close to one another[3].

Although the global statistics used in this case appear to be robust, they provide no information about local spatial variation in live-metal thefts. Anselin (1995) described a number of statistics for the study of local variation of spatial phenomena under the name local indicators of spatial association. Of those, the pre-existing G_i^* statistic (Getis and Ord, 1992) has become perhaps the most well-used in crime analysis (for example, by Mencken and Barnett, 1999; Ratcliffe and McCullagh, 1999; Ceccato *et al*, 2002; Siebeneck *et al*, 2009). The G_i^* test determines whether or not each cell in a grid is 'the centre of a group [i.e. hotspot] of unusually high values centred on [that cell] and its surrounding cells' (Chainey and Ratcliffe, 2005, p. 165), where 'unusual' is determined by calculating the probability of that number of crimes occurring by chance, expressed as a z-score. As this involves multiple comparisons between cells, the probability required before a hotspot can be considered significant must be adjusted. This was done using an equation proposed by Ord and Getis (1995, p. 297) that determined the required critical probability α_m from the number of cells n and the critical probability α that would be used for a single comparison:

$$\alpha_{\mathrm{m}} = 1-(1-\alpha)^{1/(n-1)}$$

In the present case, $\alpha=0.05$ and $n=1253$ giving $\alpha_m=4.09\times10^{-5}$, for which

$$z = 3.989.$$

Those grid cells with $z>3.989$ are highlighted in Figure 7. There are seven statistically significant hotspots, all in England, which together contain 38 per cent of all live-metal thefts reported to BTP between 2007 and 2012. The hotspots vary substantially in size and volume of crime: three (in Manchester, northeast London and the Thames estuary) had fewer than two crimes per month on average, whereas the hotspot covering South and West Yorkshire experienced 12 crimes per month over the same period (Figure 8).

To determine whether the locations of live-metal theft hotspots shown in Figure 7 were typical of railway thefts more generally, the number thefts of each type in the subsidiary data set was counted for each Voronoi polyline. Bivariate Spearman rank correlation coefficients were then calculated for pairwise comparison of the spatial concentration of live-metal theft with the concentration of each of the other theft types. A Kruskal–Wallis rank sum test showed that the distributions of the correlation coefficients for different crime types varied significantly from one another ($\chi^2=12.66$, $P<0.05$). Figure 9 shows that metal theft has the weakest correlation with other types of theft. This suggests that metal theft clusters in different places to other railway crimes. This finding may be valuable to practitioners because it suggests that police deployment patterns, shaped by exposure to long-standing crime problems such as personal robbery, may be inefficient in tackling an emerging crime

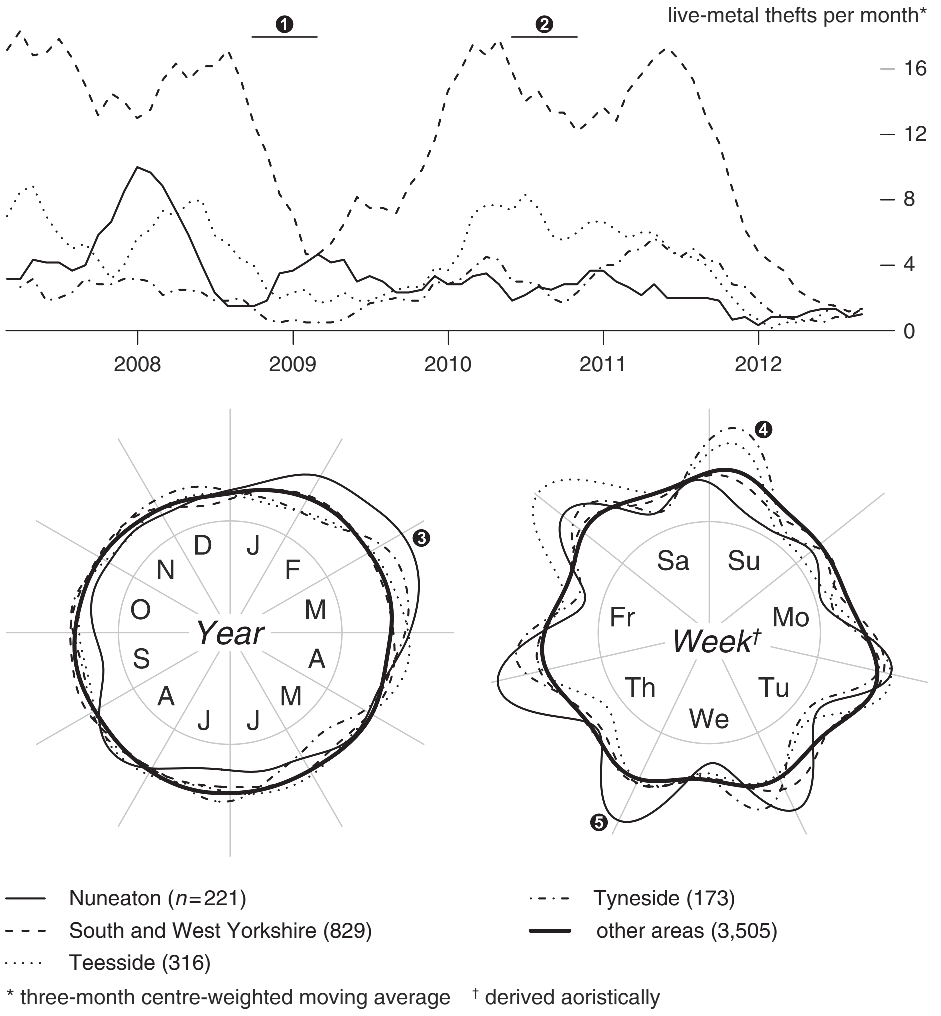

Figure 8: Temporal variation in live-metal theft from hotspots on the British railway network (2007–2012).
Notes: There appear to be differences between the temporal distributions of metal thefts at different hotspots. In particular, the number of thefts around Nuneaton went up (1 and 2) while the frequency was decreasing elsewhere. Thefts around Nuneaton are also more concentrated during the year than thefts elsewhere (3). In Teesside and Tyneside, thefts are more common on Saturday nights (4), while thefts in Nuneaton occurred on weekday evenings (5).

problem such as metal theft. As such, new patrol patterns will be required to counter this new threat to security.

Previous studies of other types of theft (for example, Rengert, 1997; Ratcliffe, 2002) have found that the temporal concentration of a single type of crime often varies across hotspots. To examine this phenomenon in relation to live-metal theft, temporal patterns were examined for those hotspots with more than two crimes per month on average, as shown in Figure 8. As temporal variation can be multidimensional, three views of the data are shown.

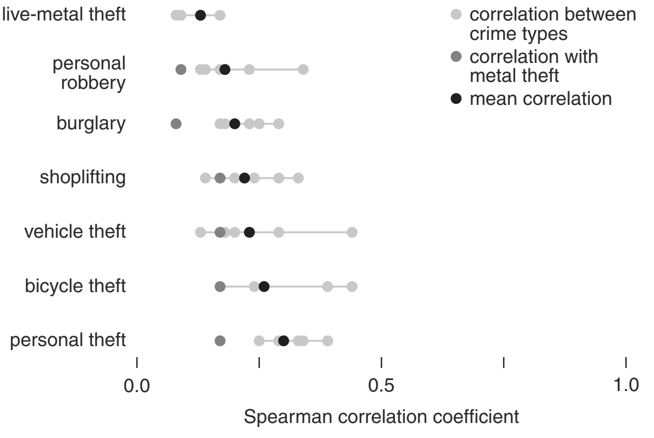

Figure 9: Spatial correlation of different types of railway thefts (2012).

The difference between the long-term trend in thefts at each hotspot and the trend outside the hotspots can be summarised using a Spearman rank correlation coefficient. All of the hotspots had trends different from those outside the hotspots, with ρ values between 0.28 and 0.62.

Testing for differences in the distribution of thefts throughout the year or the week required a test suitable for non-parametric circular data. Fisher (1993, p. 123) recommended the Wheeler and Watson (1964) test (W_r), which determines if two samples of circular data are identically distributed. The annual distribution of thefts at each hotspot was compared with the distribution of thefts outside hotspots. Only the Nuneaton hotspot had a distribution significantly different from that outside hotspots ($W_r = 0.56$, $P < 0.001$). This can be seen in Figure 8, which shows thefts around Nuneaton to be concentrated in the early months of the year. The Wheeler–Watson test was also applied to the weekly variation in thefts. This showed that weekly variation at Nuneaton ($W_r = 0.29$, $P < 0.01$) and Teesside ($W_r = 0.28$, $P < 0.01$) were significantly different from that outside hotspots.

Do Metal Thieves Plan Their Offending?

Very little is known about nature of metal theft offences. Until more is known, it may be beneficial to draw limited inferences about offences from their spatiotemporal characteristics.

One question about the nature of offences that has received only limited treatment in criminological literature is the degree to which offenders plan their offences. Most modern research on spatio-temporal variation in the occurrence of crime is based on opportunity theories developed from the routine activities approach of Cohen and Felson (1979). Within this paradigm ‘criminal events are reactions to local opportunities as they occur’ (Herbert and Hyde, 1985, p. 260), leaving open the question of the degree to which offenders will plan their offences, given that they have identified or anticipated an opportunity to offend. Offender decision-making research has found that the extent of offence planning varies widely, with 'opportunistic amateurs, journeymen who search for targets, and professionals who carefully plan their offences' (Brantingham and Brantingham, 1990, p. 26).

There is reason to think that the temporal patterns of live-metal theft discussed above suggest that offenders plan more than is typical of acquisitive criminals in general. Figure 2 and the results presented by Sidebottom *et al* (2011) show a clear link between metal price and the frequency of metal theft. The direction of causality (if any) in this link has not been confirmed, but Sidebottom *et al* (2014) ruled out influence by other variables such as unemployment and it appears unlikely that there is enough metal stolen to influence the wholesale price. If changes in prices do drive changes in the frequency of thefts, the most likely mechanism appears to be that offenders are reacting to price changes, suggesting a degree of forward planning about when to offend.

The relative lack of seasonal variation, in contrast to the strong seasonality usually found in the studies of acquisitive crime mentioned above, suggests that metal thieves are often willing to offend regardless of those factors such as weather that have commonly been found to drive seasonality. The apparent resilience of metal thieves in this regard again suggests greater planning than is typical in much acquisitive crime.

As noted above, Figure 7 shows that metal thefts appear to concentrate close to, but not in the centre of, cities. This is atypical of other types of theft, which tend to be concentrated in urban areas (Aust and Simmons, 2002). One reason for the typical urban concentration is that thieves tend to live in cities and to commit most of their offences close to where they live (Wiles and Costello, 2000; Bernasco and Nieuwbeerta, 2005), either as a result of offenders' wish to minimise the effort of offending (Bernasco and Block, 2009, p. 97) or because offenders will only be aware of targets within their awareness space (Brantingham and Brantingham, 1993, p. 10). While many theft targets such as houses, shops and banks are more concentrated in urban areas, urban railway lines tend to be well-protected by fences to stop trespassing. The concentration of thefts close to cities may suggest that urban offenders are travelling to the closest rural railway line of which they are aware in order to offend. If true, this in turn would suggest that railway-metal thieves are likely to have either a large awareness space or be planning the location of offences in advance, at least in broad terms, by pre-selecting target locations. It also suggests they need access to vehicles, which in any case would be required in order to remove metal from the railway: 100 m of copper signalling cable can have a mass of up to 200 kg (Unipart Rail, 2009, p. 12). Vehicles must either be purchased – which requires funds – or stolen – which requires particular skills and has become much more difficult in recent years (Farrell *et al*, 2011, p. 153), again suggesting at least a certain level of offence planning.

The concentration of metal theft in the early hours of the morning contrasts with other types of transport theft, which Ceccato and Uittenbogaard (2014, p. 139) found tended to concentrate at times and places when and where transport networks were busiest, that is, when there were most potential offenders present. If railway-metal theft were an opportunistic crime, it would be expected that offences would peak at busy stations at busy times. The opposite appears to be true: offenders appear not to prefer busy places and seem to wait until after midnight, when offending is aided by darkness and lack of guardianship. In this respect, metal thefts appear to be similar to robberies of transport passengers, which Clarke *et al* (1996) found clustered at stations with fewer passengers. This may explain why the spatial correlation (Figure 9) between metal theft and other types of railway theft is lower than between those other types: those committing other types of theft (except for commercial burglaries) require the presence of a person's property to steal, whereas for metal theft the presence of other people may be a deterrent.

More certain and more detailed results on the extent to which metal thieves plan their offending could be obtained using alternative methods such as offender interviews or analysis of offending histories. In the absence of such research, it appears that the theft of metal from the railway network is likely to be a planned offence rather than a highly opportunistic one. This conclusion could have implications for crime prevention because it suggests that railway-metal theft is committed by a relatively small number of repeat offenders each committing a relatively large number of crimes. Eck (2001, p. 252) argued that such repeat-offender crime problems can be effectively tackled by focusing on preventing those offenders from stealing in future. An offender-focused approach would also deal with a potential problem raised by Short *et al* (2010), who hypothesised (based on a theoretical mathematical model) that crime hotspots resulting from the activities of planned offenders were more likely to experience spatial displacement of crime as a result of police activities to eliminate the hotspot.

Conclusion

The research presented here paints a detailed picture of metal theft from the railway network of Great Britain. The spatial and temporal patterns of metal theft appear to be different from those established for acquisitive crime in general. Metal thefts occur throughout the year at approximately the same rate, in contrast to most acquisitive crimes that show strong seasonality. Metal thefts appear to be concentrated in different places to other types of theft, particularly in rural areas close to cities, rather than in cities themselves. Once a metal theft has occurred at a particular location, that place appears to be at additional risk of being victimised again for much longer than has been found for other types of crime. Perhaps most importantly for prevention, the frequency of railway-metal theft appears to be strongly influenced by the price at which offenders can expect to sell the goods for.

One reason for this is that railway-metal thefts appear to be committed by offenders who plan rather than by opportunists. It seems reasonable to hypothesise, in the absence of direct evidence, that such offenders would be more responsive to changing prices, more resilient to the changing seasons, more willing to travel long distances and more likely to return to previous offence locations. In all these ways, railway-metal theft was found to differ from other types of acquisitive crime. This planning hypothesis could be tested in future research, for example by interviewing offenders, although this may be difficult because offenders who plan (well, at least) may be less likely to be caught, introducing sampling bias into any such study.

A second reason for the unusual patterns found in metal theft may be the role of SMDs in the disposal of stolen goods; the only weeks of the year and days of the week on which there were substantially fewer metal thefts coincided with those days on which many SMDs are closed. Further research would clarify this relationship, which is particularly important because many governments have increased the regulation of SMDs in response to the increased frequency of metal theft since 2007.

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Notes

1 A point map representing stations could have been used, but this may have given the reader the impression that all thefts occurred precisely at the station itself when in fact they could have occurred anywhere within the station's Voronoi polyline.

2 The coefficients for variation for $\overline{d}$ and $\overline{\delta}$ were both 0.01, so 10 iterations were considered sufficient.

3 The NNI and Moran's *I* are subject to various limitations, as described by Unwin (1996). The problem of edge effects (described by Ratcliffe, 2005, and others) could not occur in the present research because the study area included all of the railway network. Two more important limitations are the assumption of stationarity and the MAUP.

The NNI calculated here is not subject to the MAUP, since the study area included the entire railway network. However, the 10 km cells for calculating Moran's *I* are modifiable and both Jelinski and Wu (1996) and Marchione and Johnson (2013) found that Moran's *I* values varied according to the grid chosen. To check the value of *I* produced above, the test was repeated with the cell size increased in 1 km increments from 5 km to 15 km. The resulting values of *I* varied from 0.53 to 0.66, with a mean of $I = 0.61$. These values suggest that live-metal thefts are clustered in space regardless of the effects of the MAUP.

Recent studies of spatio-temporal variation in crime have concluded that the distribution of crime is often not stationary, such that spatio-temporal analysis is likely to be more illuminating than global measures of spatial concentration.

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