A Comparison of Earthquake Hazard Modelled Results

Kevin McCue

Adjunct Professor, Central Queensland University, Rockhampton, Queensland.

Abstract

Results of a relative earthquake hazard assessment at five important sites in Australia are presented using the complete written earthquake record in Australia over the last almost 200 years that has been catalogued by intensive research over decades. The results contradict those in Geoscience Australia's recent Probabilistic Seismic Hazard Assessment (PSHA) that was based on a much shorter subset of post 1966 earthquakes, recorded on modern seismographs. The results of the two studies are in reverse order, Newcastle and Adelaide that have suffered damage and earthquake related deaths and casualties are considered in the new PSHA as at lower hazard than Canberra and Gippsland which have never suffered serious damage since European occupation.

Keywords: earthquake hazard, Newcastle, PSHA, historical earthquake

INTRODUCTION

In all regions of the globe, California to central Australia, earthquake hazard assessments are based on past earthquakes. Past earthquakes are used to define source zones and recurrence relations so crucial for modelling hazard. Only if you invoke active faults without a history of recorded earthquakes, does this dependence on history change. A combination of probabilistic and deterministic models may be used which allows a very broad range of hazard outcomes based on the assumptions made. Different analysts use different sample periods depending on their experience and comfort zones. Assumptions and weightings should be rigorously contested. No hazard analysis is “correct”.

Here we test the Geoscience Australia (Allen, 2018) PSHA model assumptions by examining historical earthquakes at five sites; Adelaide South Australia, Canberra, Moe (Gippsland) Victoria, Newcastle New South Wales and Launceston Tasmania. These sites were chosen as they are rated very differently in this latest earthquake hazard assessment to numerous previous earthquake hazard assessments.

Anecdotal accounts of earthquakes go back about 200 years at each of these sites, nearly four times the length of recorded earthquakes used for GA’s latest PSHA analysis. What’s more these anecdotal accounts can be converted into date, time location and magnitude with uncertainties that aren’t much different to early computed locations.

The method we use is that of extreme values described later, the same method widely used for flood and earthquake hazard estimations worldwide.

Both methods suffer from our lack of understanding of the tectonic processes at play, in interplate zones the location of most future large earthquakes is considered to be reasonably well known, but not the timing or size, 2 out of 3 parameters, in intraplate regions location is another unknown, alongside the timing and size of future events, 3 out of 3 parameters.

Omitting historical earthquakes from an analysis and making untestable assumptions about the rate of large earthquakes on assumed active faults jeopardises the acceptance of PSHA results, no matter how attractively the results are presented.

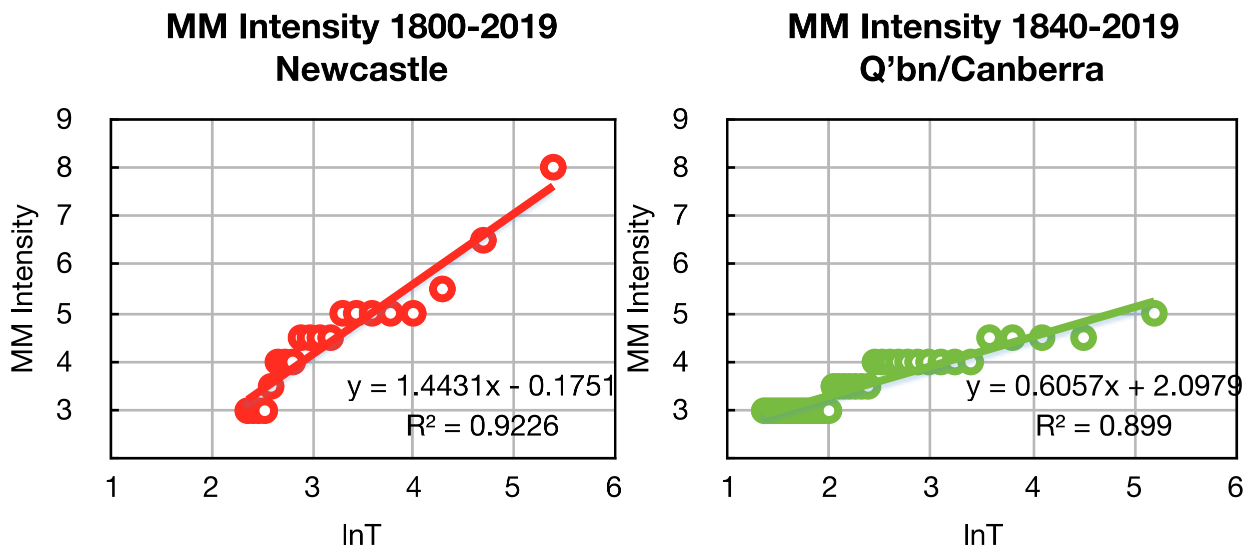
We will take the 5 source zones and look at each independently and comment on the style of seismicity before analysing the data.

NEWCASTLE NSW (FIGURE 1)

The city of Newcastle suffered the worst earthquake disaster in Australia’s short 230 year recorded history on December 28, 1989, 10 times more costly than the previous worst case, Adelaide SA, in an almost identically sized earthquake on 1 March 1954. But this wasn’t the first damaging or potentially damaging earthquake near Newcastle (see Clarke, 1869; McCue, 2014). There have been 5 previous earthquakes of magnitude 5 or more since Europeans settled the area in about 1836.

- Since 1965 there have been 33 earthquakes recorded and located within 100km of Newcastle, 5 of them of magnitude 4 or more according to the GA on-line catalogue.

- 'b' value. The local seismicity is unusual in 2 ways, there have been more earthquakes, M>4.9, than would be predicted by the frequency of smaller earthquakes or conversely few small earthquakes compared with the number of moderate earthquakes. The history is quite different to nearby Sydney, a bit more than 100km away and also in the geologically defined Sydney Basin, that has only suffered damage in the 1989 Newcastle earthquake. The 'b' value (the ratio of small to large earthquakes in the recurrence relation) appears to be quite low.



Figures 1 and 2 Historical intensities in Newcastle NSW and Canberra/Queanbeyan plotted against return period T in years using a type 1 extreme value distribution.

- Aftershocks. Most unusual is the lack of aftershocks compared with other similar sized earthquakes near Picton and Bowral in 1961 and 1973 (Cleary and Doyle, 1962; Everingham and others, 1982), the three earthquakes in the same geological environment, the Sydney Basin.

- Depth. The focal depths of well-located foci appear to be under the Sydney Basin, 10 km or more deep according to McCue et al, (1990), overlying what is thought to be the edge of the Lachlan Foldbelt, but earthquakes in the Lachlan Foldbelt near Dalton and Gunning about 340km away appear to be just kilometres beneath the surface. Dalton/Gunning is a historical NSW earthquake hotspot that has been dormant these last 30 years.

- Faults. Large ancient faults like the Hunter-Moki, Lapstone and Lake George Faults would not be deemed active based on the lack of recorded earthquakes and that goes for the many smaller faults mapped in the Sydney Basin, despite evidence for movement on them.

QUEANBEYAN/CANBERRA ACT (FIGURE 2)

Canberra, about 500km from Newcastle, is a relatively new city established in 1912 but Queanbeyan, now virtually a suburb of Canberra, has a documented history back to 1838 that can be used as an analogue for Canberra.

- Since 1965 there have been 132 earthquakes within 100km of Canberra, 4 of them of magnitude 5 or more according to the GA on-line catalogue. Some of these are swarm events, some aftershocks in the now seemingly-quiet Dalton/Gunning region.

- ‘b’ value. Small earthquakes occur under Canberra suburbs more regularly than observed under Newcastle (discounting the mine-related seismic events under Newcastle) and Adelaide, the Canberra ‘b’ value is relatively high.

- Aftershocks. There have been no earthquakes in the ACT large enough to expect aftershocks but swarms occur just over the northern ACT border in NSW. Moderate sized events have occurred in the Dalton/Gunning zone with rich aftershock sequences.

- Depth. Most of the earthquakes that affect Canberra are shallow in the upper crust, none deeper than about 10km.

- Faults. Significant faults have been mapped in the ACT by Abel and others (2000). They superposed known epicentres on the geological map showing there is no correlation of the seismicity with mapped faults. Since the late 1950s computed earthquake locations are sufficient to allocate them to known large faults but either none of the faults are active or they all are. The Lake George, Murrumbidgee, Deakin, Queanbeyan and Cotter Faults through Canberra appear to be quite inactive though some appear to have moved in the last 100,000 years.

No earthquake damage has occurred in Canberra/Queanbeyan in the last 180 years.

The most intense shaking in Canberra in the past originated from distant moderate earthquakes to the north near Dalton and Gunning, Picton and Bowral or the Snowy Mountains to the south, not from local earthquakes (Michael-Leiba, 2001).

ADELAIDE SOUTH AUSTRALIA (FIGURE 3)

Adelaide has suffered damage on three occasions since its founding in 1836. Two of the earthquakes were large distant well-studied events near Kingston and Beachport in the Southeast of South Australia in 1897 and in St Vincent’s Gulf offshore Adelaide in 1902. Two deaths in Adelaide are attributed to the 1902 so-called Warooka earthquake (McCue and McArdle, 1992). The most destructive earthquake in the 184 years occurred on 1 March 1954, the cost of damage about $120M in today’s value, a tenth of the loss in the 1989 Newcastle earthquake. Small earthquake are regularly recorded under Adelaide suburbs, many at surprising depths near 20km, in the mid crust (Love and Wallace, 2015).

- Since 1965 there have been 17 earthquakes within 100km of Adelaide, just one of them of magnitude 4 or more according to the GA on-line catalogue.

- Small local earthquakes are often felt in Adelaide suburbs so the ‘b’ value may be normal there.

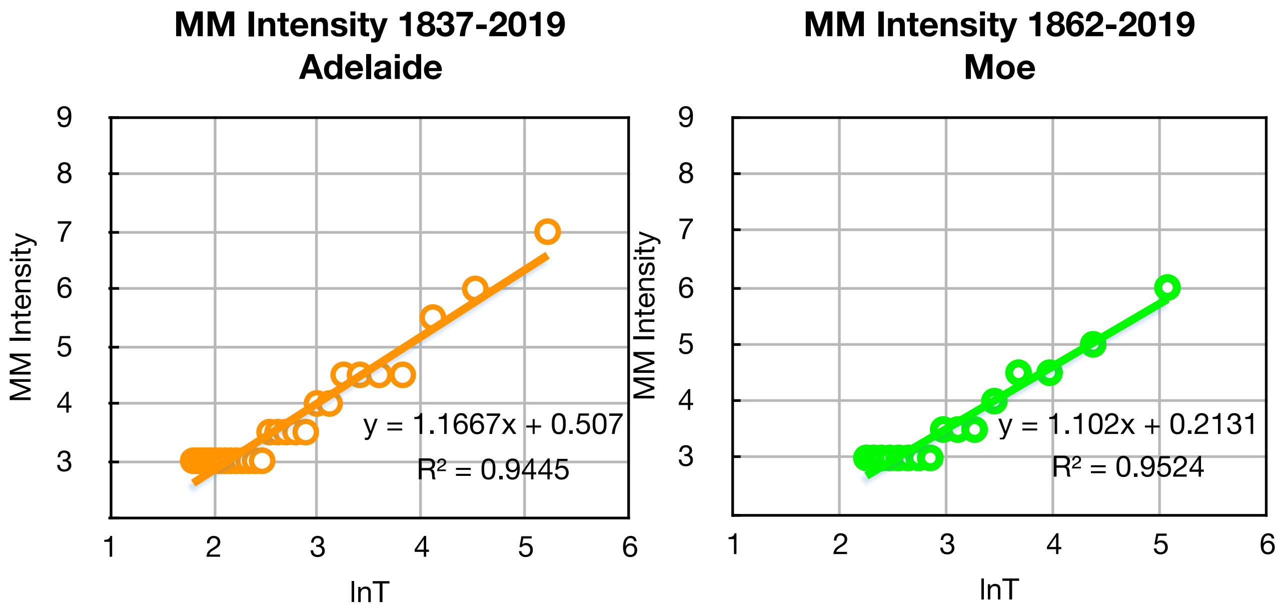
- Aftershocks. The 1902 and 1954 earthquakes in the vicinity of Adelaide had few aftershocks but those from the 1897 earthquake in the Kingston/Beachport area lasted for years.

- Depth. One surprising feature of the seismicity that has only recently been discovered thanks to an increase in the number of local seismographs (Love and Wallace, 2015) is that they often occur in the mid-to-lower crust at around 20-30 km deep.

- Faults. The Eden Burnside and Para Faults through the metropolitan area are quite spectacular and obvious features of the landscape. The 1954 earthquake has been attributed to the Eden-Burnside Fault by many authors. Paleo-seismologists trenched the adjacent Para Fault and found no evidence of recent ground rupturing earthquakes (Clark and McPherson, 2011; Love, 2013). Could one fault in a set of faults really move without movement on other conjugate faults?

MOE, GIPPSLAND VICTORIA (FIGURE 4)

There is good historical information covering Gippsland (Gibson and others, 1981).



Figures 3 and 4 Historical intensities in Adelaide NSW and Moe Victoria plotted against return period T in years using a type 1 extreme value distribution.

Minor damage has occurred on only one occasion in Moe since the late 19th century. That was during the 2012 Moe earthquake (Hoult and others, 2014). Its magnitude is similar to both the 1954 Adelaide and 1989 Newcastle earthquakes.

- 'b' value. Small earthquakes occur regularly throughout Gippsland so the recurrence relation is normal (about 1.0 over the M3 to M5 range) and comparable with that in the Adelaide region.
- Aftershocks do occur but the sequence duration is shorter than say those of Dalton/Gunning NSW.
- Focal depths of Gippsland earthquakes tend to be about 10km, most of them in the mid-upper crust.
- Faulting. Some of the larger events have been attributed to reactivation of the large ancient faults through the region (Hoult and others, 2014).

The earthquake history of Gippsland is characterised by moving clusters of small shallow earthquakes at wide-spread towns such as Moe, Korumburra, and Bairnsdale.

LAUNCESTON TASMANIA (FIGURE 5)

The earthquake history of Launceston is dramatic, so much so that NE Tasmania was included in the Circum-Pacific earthquake belt on the first world map of earthquakes (Mallett, 1858). There was an intense cluster of large earthquakes offshore NE Tasmania in 1883-1892 with 2000 felt earthquakes (Carey and Newstead, 1960). Other earthquakes, some damaging, occurred closer to Launceston in the 1920s to 1946 (Michael-Leiba and Jensen, 1992; McCue, 2015).

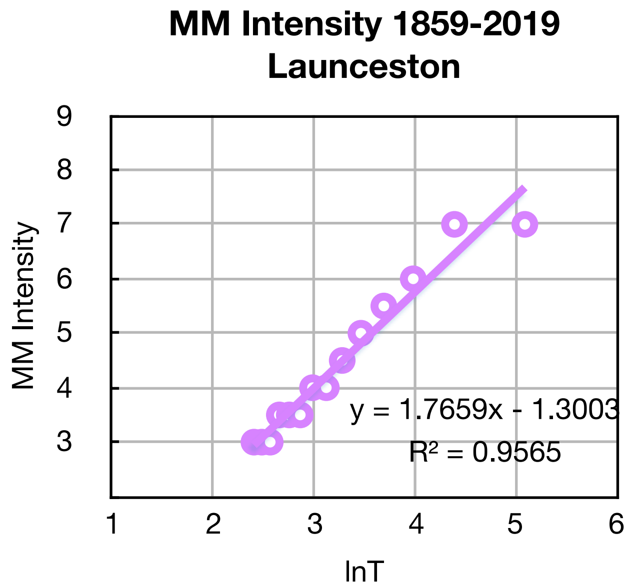


Figure 5. Historical intensities in Launceston Tasmania plotted against return period T in years using a type 1 extreme value distribution.

- Since 1965, 8 earthquakes have been recorded within 100km of Launceston, 3 of them magnitude 4 or more. Much of the early history is probably forgotten by current residents and council engineers. It couldn't happen again, could it.
- 'b' value. The area is rich in large earthquakes and their aftershocks but relatively few local earthquakes have been observed near Launceston in the post-1965 period, too few to assess 'b'.
- Focal depth. It is assumed all the earthquakes occur in the upper-middle crust but few accurate focal depths have been computed.
- Faults. Launceston is built in a large fault-bound graben-like structure, the Tamar fracture zone, and undoubtedly has suburbs underlain with soft sediments where ground shaking is intensified relative to other suburbs (Michael-Leiba, 1989). It is not known whether the earthquakes are associated with the mapped basin-bounding faults.

ANALYSIS

In this paper we use a Type-1 extreme-value method with Modified Mercalli intensity to compare the earthquake history of one Australian city relative to another and compare it with the pga rating computed by Allen and others (2018). The methodology of extreme values was introduced by Allin Cornell (1968) and used by many others engineers and seismologists including Lomnitz (1974) and McEwin and others (1976) who used it for an early earthquake hazard evaluation in Australia.

Advantages of this method are its simplicity, its lack of assumptions about zoning, focal depth, attenuation relationship or magnitude scale to contend with, just the history of past earthquake effects. It is likely that low intensities have not been reported, possible that some felt effects may have been exaggerated so the implied intensity is too high. Intensity is not a suitable parameter for design, nor is pga. But using intensity assessed by the same authority allows a straightforward relative comparison of the shaking history at different places. If anything it underestimates intensity which evolved in Europe where many buildings are old with poor masonry and mortar and inadequate foundations. According to Richter (1958), modern buildings should withstand MM8 without much damage which says a lot about the quality of buildings in Adelaide and Newcastle ($1000M damage but only intensity 8). In Australia Modified Mercalli Intensity is probably under-estimated contrary to popular myth.

So we can take the set of felt intensities, rank them in order of decreasing intensity and plot the intensity of the nth event against the natural log of the negative value of ln (j/(n+1)) or lnT where T is return period. A sampling interval of n years, n, where the largest intensity is rated n/(n+1), the next largest (n-1)/(n+1) , the next (n-2)/(n+1) etc. The return period T is ln(j/(n+1)) so on the abscissae 10 years is 2.3, 100 years 4.6 and 500 years 6.2.

Table 1 The 1, 10, 100, and 500 year return period intensities (Modified Mercalli scale) extracted from Figures 1 to 5 for the 5 sites are tabulated, the last column is the maximum observed intensity.

Return Period yrs	1	10	100	500	Max Intensity observed
Launceston	<1	2.8	6.8	9.7	7
Newcastle	<1	3.2	6.4	8.7	8
Adelaide	<1	3.2	5.9	7.8	7
Moe	<1	2.7	5.3	7.0	5+
Canberra	2.1	3.5	4.9	5.9	5

Having computed relative hazard using the extreme value method of observed intensities over the last 200 years at sites in Adelaide and southeastern Australia we can compare their ranking with the pga from a PSHA computed by Geoscience Australia (Allen and others, 2018 Appendix A) of earthquakes located in the last 50 years, in Table 2.

Table 2 Comparison of the computed 500 year return period intensities and computed 500yr pga from GA ranked by decreasing intensity.

Return Period yrs	500	
	MM Intensity	pga from GA
Launceston	9.7	0.011
Newcastle	8.7	0.022
Adelaide	7.8	0.035
Moe/Leongatha	7.0	0.07
Canberra	5.9	0.05

The ranked results are almost the inverse of each other, Canberra the highest and Launceston the lowest ranking by GA whereas our historical analysis indicates the opposite ranking.

DISCUSSION

The damage from the 1989 Newcastle and 1954 Adelaide earthquakes taught us how destructive earthquakes can be if they are sufficiently large and if they occur near an urban area. This message was rammed home after the series of earthquakes at Christchurch NZ in 2010/11 where the largest earthquake was not the most destructive. It is tempting to think that only poorly constructed or only masonry buildings are vulnerable to damage and that is probably the majority of buildings in Australia; they aren't designed or built for horizontally applied dynamic forces.

The Newcastle Workers Club was in this category and it was soon demolished. Christ Church Cathedral, previously damaged in the 1925 earthquake, was so badly damaged that the initial response of authorities was to demolish it too. Many other historical buildings and 35,000 homes were badly damaged resulting in 13 deaths, 1000 displaced people and a $4 billion damage bill.
Damage on this scale is unprecedented, only in Adelaide in 1954 and at Meckering WA in 1968 was damage extensive. Only Adelaide and Newcastle have been damaged in at least 2 separate earthquakes. But modern buildings and infrastructure are vulnerable too as demonstrated at Tennant Creek NT in 1988.

Figure 6. (above) The partially collapsed Workers Club, (below) the Kent Hotel. (photos from the Newcastle Library collection).

The State Government library in Newcastle has thousands of photographs of the damage inflicted on Newcastle. One must be careful. Some of the photos were taken after demolition had begun. Other photographs of earthquake damage can be downloaded from the AEES website (www.aees.org.au). There has been nothing like this level of damage in Moe Victoria or Canberra, or any other city in Australia.

Earthquakes occur whether they are recorded on a seismograph or not. The 1906 San Francisco earthquake was recorded on few seismographs, has had its magnitude significantly downgraded but it would never be omitted from a Californian hazard analysis. The 1811-12 earthquakes in New Madrid, Missouri were not recorded on seismographs but similarly would not be ignored, nor the nearly 2000 year history of earthquakes in China, the 1000 year history of earthquakes in Europe. So why are the historical earthquakes of Australia not utilised by GA analysts? Completeness issues lead to them being removed, so they don't contribute to zoning nor are they used in the recurrence relation calculations. Categorising those early pre-instrumental earthquakes and ascribing location and magnitude is an art. Location, focal depth, origin time and magnitude all are required for modern catalogues and PSHA. But the intensity based earthquake catalogues are equally useful and extend by hundreds or in some case thousands of years the modern instrumental catalogue. Magnitudes and locations can be derived for the well reported ie larger events.

It should not be conveniently overlooked that the production of modern earthquake catalogues is also an art. Different analysts obtain different locations, often they assign rather than accept the computed focal depth, they compute magnitude using any of the multiple scales on offer and convert from one scale to another multiple ways, and even change the value measured. It is not unusual even now to have a range of nearly one magnitude unit in measured magnitudes for a single event between agencies, even within one agency from one station to another.

So why are the analyses reported here and by Geoscience Australia so different and if one of the studies is correct, which one? The answer is that the outcomes reflect the assumptions made, as simple as that. If you ignore past earthquakes, in Launceston for example, then the implied seismicity is zero and resultant computed hazard negligible. On the other hand if there is no observed seismicity but you assume an average rate of large earthquakes based on limited paleoseismology information then the results simply reflect that assumption as in the case of Canberra. Strictly speaking neither is likely to be correct - to predict the actual seismicity of the next 50 years from the past 50 years is based on the underlying assumption of some kind of average earthquake rate based on cycles, periods of active seismicity followed by gaps in seismicity. The predicted and actual earthquake occurrence would probably be much closer if modern PSHA analysts incorporated macroseismic data into their PSHA analysis rather than ignore them, after all these databases do exist.

Earthquakes don't occur at regular intervals, anything but. However over a long enough time interval some cyclic nature may be observed, short active periods separated by long quiet periods. What is an earthquake cycle and how are they defined? Until you have gone through several cycles you don't know how long they are, or even if they exist. The implication of the following article is that earthquake cycles don't occur in California or if they do then it is not helpful because we don't know what they are.

> *California is in an earthquake drought*
> *By Rong-Gong Lin II Apr 02, 2019*
>
> *https://www.latimes.com/local/lanow/la-me-ln-earthquake-drought-storm-20190402-story.html*
>
> *It has been almost five years since the state experienced its last earthquake of magnitude 6 or stronger — in Napa. Southern California felt its last big quake on Easter Sunday 2010, and that shaker was actually centered across the border (ed. Mexican border), causing the most damage in Mexicali.*

> *Experts know this calm period will eventually end, with destructive results. They just don't know when this well-documented geological pattern will shift.*
>
> *Earthquake rates are quite variable: We have a decade or two where we don't have many earthquakes, and people expect that's what California is always like," said Elizabeth Cochran, seismologist with the U.S. Geological Survey. Eventually, "we're going to dramatically see a change in earthquake rates.*

So if the USGS don't know how long the cycles last on an active plate boundary we can't claim to know in intraplate Australia with an even shorter record. Dare we claim Tennant Creek NT had its earthquakes and now is turned off for thousands of years, the same at Meckering WA, or NE Tasmania or Adelaide SA. That nothing is causing these hotspots? About all we can say is that these areas hosted large earthquakes in the immediate past and should be considered to be in an active phase unless proven otherwise. The stress drop during these large earthquakes hardly changes the in-situ stress, so the hazard there should be rated higher than elsewhere, not lower.

The next Australian PSHA should incorporate the published historical data, especially the large events. More works needs to be done on mapping recent surface faults and assessing their history. In the meantime we must acknowledge that Australia does host potentially damaging earthquakes and we need to design and build for them, everywhere. It isn't difficult and need not be expensive. It is the psychological barrier that needs to be breached not the engineering challenge.

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