Benefits and Costs of Earthquake Early Warning

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ABSTRACT

Earthquake early warning (EEW) is the rapid detection of earthquakes underway and the alerting of people and infrastructure in harms way. Public warning systems are now operational in Mexico and Japan, and smaller-scale systems deliver alerts to specific users in Turkey, Taiwan, China, Romania, and the United States. The warnings can arrive seconds to minutes before strong shaking, and a review of early warning applications around the world shows this time can be used to reduce the impact of an earthquake by many sectors of society. Individuals can use the alert time to drop, cover, and hold on, reducing injuries and fatalities, or if alert time allows, evacuate hazardous buildings. Train derailments can be reduced, chemical splits limited, patients in hospitals protected, fire ignitions prevented; workers in hazardous environments protected from fall/pinch hazards, reducing head injuries and/or death. It is impossible to complete an exhaustive list of applications and savings generated by a warning system in the United States, but the benefits clearly outweigh the costs. Three lives saved, two semiconductor plants warned, one Bay Area Rapid Transit train slowed, a 1% reduction in nonfatal injuries, and a 0.25% avoidance of gas-related fire damage would each save enough money to pay for 1 year of operation of a public warning system for the entire U.S. West Coast. EEW could also reduce the number of injuries in earthquakes by more than 50%.

INTRODUCTION

Earthquake early warning (EEW) can provide a few seconds to a few minutes of warning prior to ground shaking at a given location. EEW is used publically, and prototypically, in several countries around the world, with the aim of reducing the damage, costs, and casualties resulting from an earthquake. Actions taken in response to the alerts range from personal safety approaches (such as drop, cover, and hold on) to automated controls and situational awareness. In this article, we provide a summary of the status of EEW around the world for the nonspecialist and provide examples of cost-saving response actions. This article is intended for prospective users of early warning, government officials setting policies, and others outside of the seismological community, illustrating the broad landscape of mitigation possibilities that early warning provides.

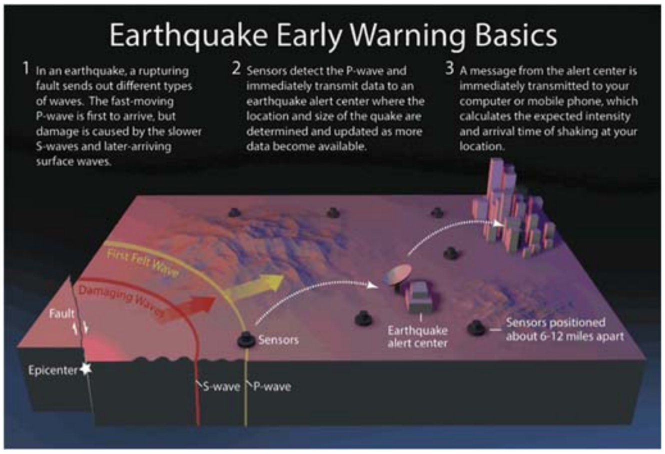
Unlike seismic retrofits, where a direct cost–benefit of damage reduction is readily made, early warning mitigates many hidden costs that are difficult to monetarily delineate but are ultimately crucial for long-term resiliency postrupture. Attempts to calculate potential annual loss reductions specifically resulting from EEW actions are difficult, due to the fact that few outside of the seismological community are aware of the technical capabilities. For that reason, we here illustrate known possible savings from EEW and show that EEW can aid in mitigation for broad-risk categories, including reducing train derailments and chemical spills, isolating radioactive sources, protecting patients, reducing fall/pinch hazards, and reducing head injuries and/or death. Though we cannot *a priori* determine which individual risks will occur in any given earthquake, the savings are so significant and so diverse that a robust EEW system would be a good return on investment. Saving three individual lives, or alerting two semiconductor plants, or preventing the derailment of one Bay Area Rapid Transit (BART) train, would each individually save enough money to pay for one year of operation of the system for the entire U.S. West Coast. The savings are not limited to just the risks outlined in this article, even though these alone would be sufficient to justify the costs of a warning system.

EARTHQUAKE EARLY WARNING

EEW, like warnings for other natural disasters such as tornadoes, hurricanes, and tsunamis, is a forecast of activity that is imminent. However, unlike hurricane warnings, which can come days in advance of severe weather, or tsunami warnings, which build over the course of a few minutes to a few hours before the tsunami makes landfall, earthquakes have a much shorter lead time, shorter even than a funnel cloud that starts spiraling toward the earth. A warning could be just seconds.

This short warning time is a product of the physical process of an earthquake rupture. A schematic regional EEW system

doi: 10.1785/0220150149



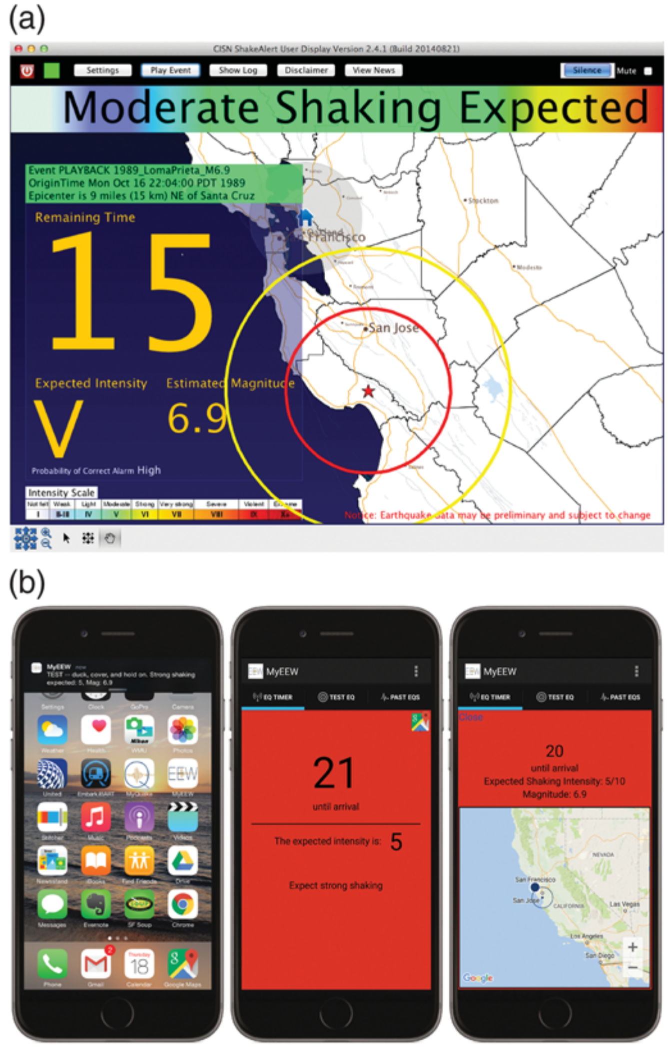
▲ **Figure 1.** Representative illustration of the regional earthquake early warning concept. Provided by Erin Burkett (U.S. Geological Survey [USGS]) and Jeff Goertzen (Orange County Register).

is outlined in Figure 1. In essence, EEW uses seismometers to detect the first signature of an earthquake (*P* wave, yellow arc), to process the waveform information, and to forecast the intensity of shaking that will arrive after the *S* wave (red arc). For local EEW installations, the *P* wave is detected onsite (i.e., at the user location), and the difference between the *P*- and *S*-wave arrival times defines the maximum alert time. For regional networks, the *P* waves are detected by sensors closest to the epicenter, and estimates are immediately relayed to earthquake alerting applications (TV, smartphones, radio, etc.) to provide businesses, citizens, and emergency responders more advance knowledge of the expected arrival and intensity of shaking at their location.

Heaton *et al.* (1985) proposed a model for a computerized seismic alert network, which laid the groundwork for the EEW systems in place around the world today. They proposed that this computer-backed system could protect hazardous chemicals, initiate electrical isolation, and protect fixed-rail transport systems, hospitals, fire stations, etc. These ideas have now been tested, and some are operational for several EEW systems globally.

EEW AROUND THE WORLD

The U.S. Geological Survey (USGS), in partnership with the University of California at Berkeley, the California Institute of Technology, and the University of Washington, with support from the Gordon and Betty Moore Foundation, created an EEW initiative called ShakeAlert (Fig. 2). This system incorporates existing sensors from the California Integrated Seismic Network and the Pacific Northwest Seismic Network and sends alerts to a cadre of test users—over 50 groups including the BART, the cities of San Francisco and Los Angeles, Boeing, and Intel. It is currently an end-to-end demonstration system, and conversion to a more redundant and robust production prototype is underway, with a view toward limited rollouts



▲ **Figure 2.** (a) ShakeAlert UserDisplay showing a snapshot of the warning from a simulation of the 1989 Loma Prieta earthquake. The red star is the epicentral location, and the yellow and red circles are the *P* and *S* wavefronts. The key alert information is the shaking intensity and time of the *S* wave (representing onset of strong shaking) at the user's location. This is the warning at University of California, Berkeley, as indicated by the location of the blue house icon. The UserDisplay is a java-based application that can run on any computer and is available to ShakeAlert test users. (b) MyEEW smartphone app for the same scenario event. An audible alert with the shaking intensity at the user's location is first received automatically (top of left screenshot). When the user touches the notification, a simple screen shows the expected shaking intensity at the user's location and counts down until the *S*-wave arrival (middle screenshot). By touching the "Map" link (top right) a screen with more information is displayed showing a map of the event and user location and the magnitude, in addition to the shaking intensity and countdown (right screenshot).

in the near future. The system currently combines single-station algorithms (OnSite, Bose *et al.*, 2012), with multistation approaches (ElarmS, Serdar Kuyuk *et al.*, 2013; Virtual Seismologist, Cua *et al.*, 2009) to provide the quickest and most accurate alerts possible. Speed is critical for the U.S. West Coast, because fault lines and their associated hazards coincide with areas of high population density. Learning from other systems in operation today worldwide, the ShakeAlert project also augments the traditional seismic results with Global Positioning System (Grapenthin *et al.*, 2014a,b) and Bayesian approaches (Bose *et al.*, 2014).

ShakeAlert successfully alerted test users for both the 2014 **M** 6.0 South Napa earthquake (Brocher *et al.*, 2015; Dreger *et al.*, 2015) and the 2014 **M** 5.1 La Habra earthquake (Hauksson *et al.*, 2014). The BART system in San Francisco activated its hazard mitigation protocol, which triggers trains to automatically slow or stop, depending on predetermined conditions. However, no trains were running at 3:20 a.m. when the Napa earthquake occurred.

Mexico is home to the oldest public EEW system in the world. The effort began in 1991 with Mexico's strong-motion accelerometer network, which monitored large subduction zone earthquakes off of the western coast and alerted citizens of Mexico City that heavy shaking was on its way. El Sistema de Alerta Sísmica Mexicano (SASMEX) now sends alerts to Mexico City, Oaxaca, Acapulco, Chilpancingo, and most recently Morelia via TV, AM/FM radio, National Oceanic and Atmospheric Administration weather radios, and the Mexican Hazard Alert System (Espinosa-Aranda and Petel, 2014). In 2009, the 230 registered users for the system were surveyed, and 91% respondents considered EEW a useful tool for their institution as a civil protection measure and maintain a positive view of the system as a whole (Suarez *et al.*, 2009). The city of Acapulco received 24 s of warning from SASMEX for the **M** 7.2 Guerrero earthquake on Good Friday, 2014. Mexico City (situated almost 400 km away) was provided more than 68 s of early warning (see Data and Resources).

The Japanese EEW system successfully alerted several million people near the epicenter, providing 15–20 s of early warning, for the 2011 **M** 9.0 Tohoku-Oki earthquake and tsunami (Fujinawa and Noda, 2013). Ninety percent of the people alerted were able to take action in response to the warning to aid in their survival; this high rate of effectiveness was a result of EEW education and training (Fujinawa and Noda, 2013). Post-earthquake surveys indicated that almost 80% of respondents were alerted by the EEW and were prompted to take action. About 82%–91% of respondents (the rate varies depending on the survey group) thought favorably of the EEW system. The system has been in operation since October 2007 and is arguably the most advanced EEW system in the world. The alerts and automated responses are tied into the high-speed rail infrastructure, schools, and businesses, and many private sector groups provide value-added services to augment the public alerts provided by the Japan Meteorological Agency.

In June 2015, the Chinese government approved a project to construct EEW systems in four large regions of the country: north China, southeast Coastal, the north–south seismic belt, and northwestern Xinjiang. The project builds on demonstrations systems that have been running in the Capitol City Zone, Lanzhou City, and the Fujian Province for several years. The project will deploy 2000 broadband and strong-motion seismic stations, an additional 3000 strong-motion sensors, and it plans to start delivering warning by 2020.

The Seismic eArly warning For EuRope (SAFER) and Real-time EArthquake risK reducTion (REAKT) projects involved many institutions in Europe funded to explore the possibility of warning across Europe. A system in Bucharest, above the deep Vrancea subduction earthquakes, provides a preliminary shake map to a nuclear research facility within 4–5 s of the origin time (Zschau *et al.*, 2009). A regional EEW system is undergoing testing in the Irpinia region east of Naples and could provide 8–16 s warning to the city (Zollo *et al.*, 2009). EEW was implemented in Istanbul in 2002 in response to the 1999 earthquakes. The system provides traffic control for the Fatih Sultan Mehmet suspension bridge and Marmaray tube tunnel across the Bosporus Straits as well as the regulator stations and natural gas valves for the Istanbul Natural Gas Distribution Network (Alcik *et al.*, 2009). Finally, a demonstration warning system is operational in Switzerland, and alerts are being delivered to nuclear power plants (Cauzzi *et al.*, 2014).

Other groups worldwide are also working toward better earthquake response through early warning. Taiwan is currently testing its own EEW system, with alerts sent to users in the railway and disaster-prevention sectors. Hsiao *et al.* (2009) discussed that, between 2001 and 2009, 225 alerts were generated for events greater than **M** 4.5 both inland and off the coast, with a latency time of 20 s after the origin time of the earthquake (Hsiao *et al.*, 2009). Israeli Seismic Network scientists are working with University of California, Berkeley, to implement the Earthquake Alarms Systems (ElarmS) algorithm in Israel. The system is running in both real time and in real-time playback modes with a new visualization tool called ElarmS Visualization System (ElViS). As the technology gains deeper global penetration, inhabitants of other high-fault-hazard zones will begin looking toward EEW as a possible solution to their own risk exposure.

HAZARD MITIGATION AND EEW

Risk exposure refers to the potential loss of life, personal injury, economic injury, and property damage resulting from natural hazards by assessing the vulnerability of people, buildings, and infrastructure to natural hazards (Federal Emergency Management Agency [FEMA], 2014). EEW is a tool that can reduce risk through personal preparedness, situational awareness, and automated controls. Personal preparedness (including drop, cover, and hold on) prevents the most common injuries during an earthquake—those resulting from falling and flying objects—and increases the safety of the population, particularly in schools and public places (Zschau *et al.*, 2009; Earthquake Country Alliance, 2014a). The elderly and persons with disabilities are disproportionally affected by natural disasters and, as such, could most directly benefit from early warnings and a clear preparedness plan (Brittingham and Wachtendorf, 2013; Earthquake Country Alliance, 2014b). Situational awareness provided by EEW allows civil protection authorities advance notice for more rapid and efficient mobilization and adaptable response (Zschau *et al.*, 2009). Awareness of the location, extent, and intensity of the coming shaking allows responders to assess the impact and their potential next steps.

Protecting critical structures (e.g., hospitals, air traffic control facilities, schools, and businesses) through EEW-automated controls allows them to remain operational and is crucial for long-term resiliency. Earthquake-induced secondary effects (e.g., fires and industrial accidents) are reduced through the application of computer-initiated controls that can safeguard operations, transport systems, and lifelines, thus allowing social facilities to return to normal as soon as possible (Heaton *et al.*, 1985; Zschau *et al.*, 2009).

Hospitals

Since 2003, EEW actions in a hospital setting have been implemented and tested at the National Hospital Organization Disaster Medical Center in Japan. Stopping surgery safely and temporarily disconnecting ventilator tubes are easy and highly effective ways to prevent fatal errors in the emergency room during an earthquake (Horiuchi, 2009). Opening doors to provide egress routes, closing blinds/curtains to minimize glass debris, and raising awareness of falling hazards aid in reducing risk to both staff and patients. Securing radioactive sources and bringing equipment into a safe mode can also effectively protect people in radiography departments. In the operating room, staff can stabilize a patient quickly and easily in response to an early warning. Hazard mitigation plans involving EEW for hospitals must consider the proximity of their staff to the actions they need to implement as well as the time required to complete said actions for each department independently.

Schools

Schools are another sector where staffs need to protect themselves as well as a vulnerable population. General protective measures such as closing curtains to prevent injuries from broken glass, opening classroom doors to ensure egress, and raising awareness of falling hazards are applicable for schools just as it is for hospitals. Many schools in Japan are equipped with EEW, and installation in all schools is underway (Fujinawa and Noda, 2013). Schools receive arrival time and seismic strength information and forward alerts to loudspeakers, announcement systems, and TV receivers in classrooms (Motosaka and Homma, 2009). On 14 June 2008, the staff of the junior high school in Shiroishi City (110 km from epicenter of the **M** 6.9 Iwate–Miyagi Nairiku earthquake, Japan) took action with 21 s of early warning, allowing 102 students (including 10 disabled students) to drop, cover, and hold on to avoided injury.

Police, Fire, and Other Emergency Response Groups

Police, fire, and other emergency-response groups may be involved in rescue efforts and cleanup operations that may be compromised by aftershocks. Opening firehouse bay doors in advance of shaking to prevent jamming and activating municipal Emergency Operations Centers before communications are lost aids response. Fire and Police departments also benefit from situational awareness of the forecasted severity of the shaking. Often, first responders rely on mutual aid from outside areas to augment their efforts. Simply knowing in advance which municipalities are going to be affected and which ones could be called upon for assistance helps to streamline the process after the event, particularly if communications become disabled.

Elevators

During heavy shaking, an elevator car and counterweight can move out of alignment becoming jammed. Elevator stoppage through earthquake detection or early warning protects the occupants and system. Almost half of the elevators Otis maintains in Japan are already equipped with earthquake detectors, which return the elevators to the ground floor when strong shaking is detected so passengers can exit (Layne, 2011). Some 16,700 elevators performed an emergency shutdown during the Tohoku-Oki earthquake in 2011, which meant that first responders did not have to devote time and resources to rescue any trapped or injured passengers (Layne, 2011). Other elevators are linked to EEW systems, allowing safe shutdown before strong shaking starts. further protecting occupants.

Manufacturing

The best-documented example of manufacturing resilience due to EEW comes from the OKI semiconductor factory in Miyagi Prefecture, Japan. Early warning alerts trigger isolation of the hazardous chemical systems and prompt the lithography tables to move to a safe position in advance of shaking (Allen *et al.*, 2009). Several automated controls in a manufacturing context reduce cascading failures, such as shutting off gas valves to prevent secondary hazards and protection of personnel. The Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania, prevents cascading failure by automatically securing their nuclear source (Ionescu *et al.*, 2007).

Other Lifelines

Predetermined risk scenarios used in conjunction with EEW (Pittore *et al.*, 2014) provide lifelines and emergency responders a framework of immediate estimates of damage types and locations. Municipalities could assess activation of mutual-aid deployment to/from neighboring cities. The Salvation Army could predetermine which divisions would be impacted under various earthquake scenarios and implement planning and response accordingly (John McKnight, Director of Emergency and Disaster Services the Salvation Army, personal comm., March 2015). Real-time seismic motions for lifelines such as dams could be compared with predetermined models to inform disaster prevention actions in the aftermath of an earthquake (Pagano and Sica, 2012). These actions include the monitoring of earthquake-induced effects, characterization of dam safety conditions, and alarming those nearby to reduce exposure.

Alerts can also trigger rapid checks of dam safety conditions with regard to possible collapse scenarios.

Transportation Systems

Transportation systems including airports, railways, and roadways are important to safeguard with EEW, not only to protect passengers but also to ensure the smooth flow of goods needed for recovery efforts in and out of the impacted area. For airports, personal safety within the terminal would center on drop, cover, and hold on. Outside the terminal, air traffic controllers with the situational awareness of a coming event can better manage air traffic. Planes can stop taxiing; baggage handlers can get away from hazardous situations; and planes on approach can go around until the shaking is over and the runways have been inspected.

The BART in San Francisco is the first transportation system in the United States with an end-to-end early warning system. BART uses both the ShakeAlert system and on-track accelerometers (set to trigger at a defined threshold of $0.1g$) to slow and/or stop the trains in safe configurations. On 24 August 2014, the **M** 6.0 South Napa earthquake shook the Bay Area at 3:20 a.m. The BART operations center in Oakland, California, received 8 s of early warning before the *S*-wave arrival. The system preformed as desired; however, no actions were ultimately taken, because no trains were running at the time.

The Shinkansen high-speed trains in Japan have an impressive track record of performance in earthquakes, due to engineering controls for the trains and EEW. No passengers or staff were injured during the Great Tohoku earthquake in 2011, and only one train running in test mode derailed. The *S*-wave detector at Cape Kinkazan triggered (120 Gal threshold), and the emergency brakes were automatically applied to all 33 trains. The first tremors hit the trains nearest the epicenter in Sendai 9–12 s after the alert, whereas the strongest shaking took another minute to arrive (Shimamura and Keyaki, 2013).

Railways also benefit from warnings that arrive too late to fully complete automated controls—as seen during the 2004 Niigataken Chuetsu earthquake. Train Toki 325 traveled into the affected region and was jolted by the *P* wave without warning. It received an alarm from the Compact Earthquake Detection and Alarm System (UrEDAS) 0.6 s later, and the power supply was interrupted to slow the train. The driver applied the emergency brake 1.5 s later after recognizing the Compact UrEDAS alarm and 1.2 s later the heaviest shaking began—not nearly enough time to fully slow the train from 204 km/h to a safe speed. Although the train did ultimately derail, the EEW provided crucial 1.2 s to slow the train before peak shaking and thus the derailment was noncatastrophic (Nakamura, 2008).

Drivers on roadways may be unable to identify the shaking as coming from an earthquake, so alerts on signage can bring awareness and prompt actions such as preventing motorists from entering bridges and tunnels. The California Department of Transportation (Caltrans) made use of an EEW system to protect workers during the small but hazardous (due to all the unstable debris) aftershocks of the Loma Prieta earthquake. The radio receiver at the Caltrans headquarters at the damaged Cypress St. section of the I-880 freeway in Oakland received a 20 s warning before the **M** 4.5 aftershock on 2 November 1989. In the first six months of operation, the system generated triggers for all twelve $\mathbf{M} > 3.7$ aftershocks for which trigger documentation is preserved, did not generate triggers on any $\mathbf{M} \le 3.6$ aftershocks, and produced only one false trigger (Bakun *et al.*, 1994).

COSTS AND BENEFITS

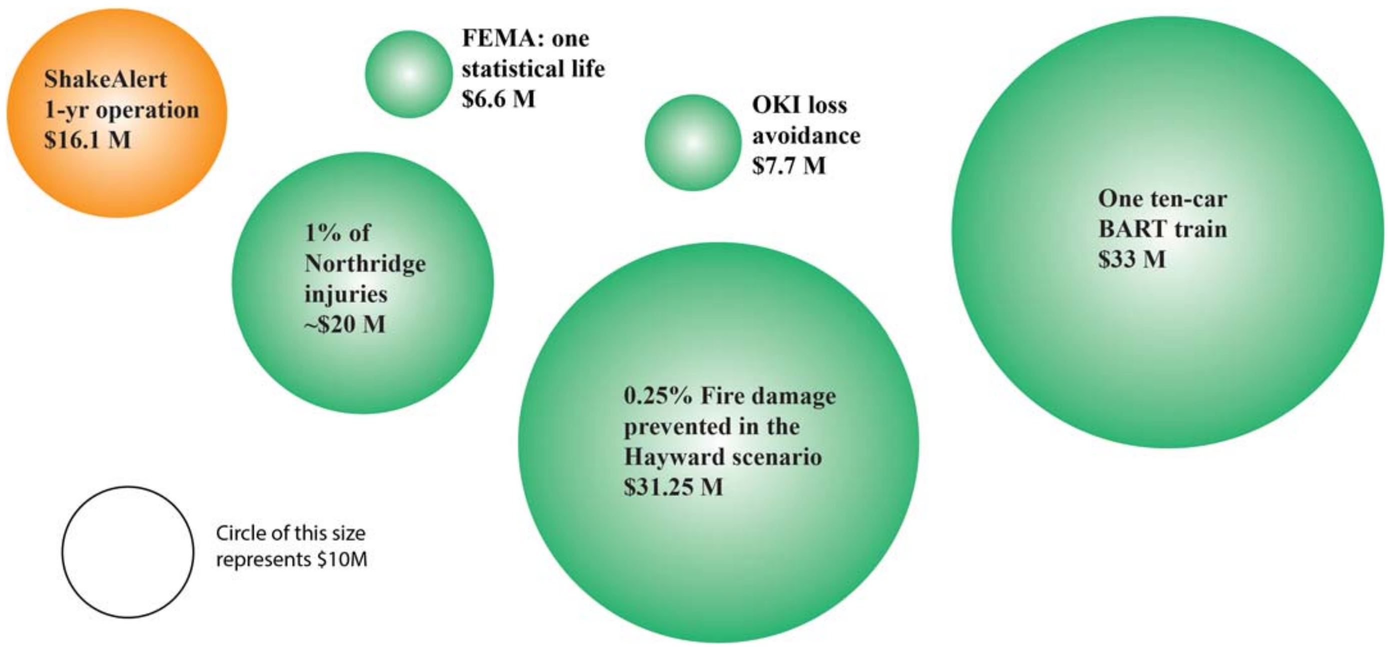
A fully implemented public warning system for the West Coast of the United States would cost \$16.1 million per year above the current USGS funding levels for the Earthquake Hazards Program (see Fig. 3), which would finance personnel to run the system, ongoing improvements and upgrades for the instrumentation, and continuing research and development (R&D) to maintain state-of-the-art alert methods. This does not include one-time costs of \$38 million to increase the station density of the existing networks and upgrade old seismometers to current standards (Burkett *et al.*, 2014; Given *et al.*, 2014).

The costs are well defined. The savings are envisioned through a varied landscape of possibilities. Previous cost–benefit studies in California were assembled before the Internet and trust in automated controls (Holden, 1989). Now society not only counts on automation as a part of daily life, but we have a wealth of information from other countries and their experience with early warning to inform our choices.

In both the 1989 Loma Prieta and 1994 Northridge earthquakes, more than 50% of the injuries were caused by falls and falling hazards (Shoaf *et al.*, 1998). This includes all the injuries caused by nonstructural hazards such as falling ceiling tiles, lighting fixtures, bookcases, and so on. If everyone received a few seconds of warning, and if everyone dropped, took cover, and held on, then early warning could reduce the number of injuries by more than 50% in future earthquakes. Porter *et al.* (2006) estimated the cost of injuries in the Northridge earthquake to be \$1.8–2.9 billion (in 2005 equivalent dollars), so EEW could provide \$1–1.5 billion in savings in a future similar event.

The cost of injuries represents 3%–4% of the estimated \$50 billion in direct capital losses and direct business interruption losses. Taking this 3%–4% ratio as indicative of future events, the economic value of future earthquake injuries—the amount that the U.S. government would deem appropriate to expend to prevent all such injuries—is on the order of \$200 million per year (in 2005 dollars, based on the \$4.4 billion expected annual loss due to earthquakes each year (Porter *et al.*, 2006). The cost of EEW is \$16.1 million per year; a mere 1% reduction of the injuries in the Northridge earthquake is equivalent to the cost of the system for 1 year (see Fig. 3).

According to FEMA's cost–benefit methodology for hazard mitigation projects, the current value of a statistical life in the United States is \$6.6 million (see Fig. 3). Therefore, it stands to reason that if three deaths per year, on average, are avoided through implementation of EEW, the system pays



▲ **Figure 3.** Comparison of the cost of running a U.S. West Coast early warning system (orange) with some of the identifiable savings (green). All disks are scaled relative to the white disk representing $10 million.

for itself (John D. Schelling, Interim Mitigation & Recovery Section Manager Washington Military Department, Emergency Management Division, testimony before the United States House Committee on Natural Resources, Subcommittee on Energy and Mineral Resources, 10 June 2014).

One of the best documented returns on investment for private industry is that of the OKI semiconductor factory in Miyagi Prefecture, which experienced $15 million U.S. in losses due to fire, equipment damage, and loss of productivity in two moderate earthquakes (**M** 7.1 and 6.4) in 2003. They invested $600,000 U.S. in retrofits and EEW controls to automatically shut down hazardous chemical systems and manipulate sensitive equipment into a safe position. In two similar subsequent earthquakes, the losses were reduced to only $200,000 U.S. (Allen *et al.*, 2009), a savings of $7.7 million U.S. per earthquake (see Fig. 3). There are over 1000 semiconductor companies in California alone (see Data and Resources), thus protecting just two of them annually with EEW and retrofits would pay for the system as a whole.

The Reliability Engineering group for the BART analyzes passenger flow models for the entire system. Taking Tuesday, Wednesday, and Thursday averages from 7:00 a.m. to 6:30 p.m., 30–40 trains are moving at any given time, totaling 300–400 individual cars in motion (Kevin Copley, Manager of Computer Systems Engineering at BART, personal comm., March 2015). Preventing derailment of one single train during the workday could save 10 individual rail cars. At a total project cost of $3.3 million per car, that translates to a possible $33 million of savings, equivalent to 2 years of operation of ShakeAlert (see Fig. 3). This calculation considers just the cost for train-car replacement alone; the cost savings of avoiding injuries to passengers would increase the benefit substantially. As an example, the 12 May 2015 derailment of the Philadelphia, Pennsylvania, Amtrak train number 188 resulted in 8 fatalities and 200 injuries at a cost in excess of $9.2 million (National Transportation Safety Board, 2015).

Other transportation sectors have similarly large assets to protect. The cost of a single modern airplane, such as the Airbus A318 with a list price of $74 million (see Data and Resources), is well in excess of the cost of a 10-car BART train. Protecting such large capital investments though the use of an early warning system to divert planes on approach during heavy shaking could reduce the risk of a costly crash, not only in the monetary terms for the plane itself, but also for the crew and passengers who would remain safely on board.

In both the United States and Japan, fire was the single most destructive seismic agent of damage in the twentieth century (Scawthorn *et al.*, 2005). For an **M** 7 earthquake on the Hayward fault, the loss estimates to fire are around $50 billion (Charles Scawthorn, after Fires and the Hayward Earthquake Workshop, written communication, October 2014). This loss quantity only considers the residential and building replacement value. The total number of ignitions is estimated to be around 1000, with 25% of those stemming from gas connections and underground lines. Some gas valves during the 1994 Northridge earthquake had seismic shut-offs installed, which helped reduce ignition (Scawthorn *et al.*, 2005); implementation of EEW-based shut-offs would be able to boost their effect. If only one quarter of 1% (0.25%) of the damage due to gas-related ignitions could be prevented by early warning, a savings of $31.25 million could be realized (see Fig. 3).

CONCLUSION

Implementation of EEW systems is increasing around the world: Mexico, Japan, Europe, Israel, Taiwan, China, and now the United States, all have systems and provide alerts to users. There are now real-life demonstrations of the benefits of EEW. Building occupants in Mexico are able to evacuate structures that are likely to collapse in an earthquake. School children took shelter during the 2011 Tohoku-Oki earthquake. Trains can be slowed to reduce the risk of derailment. Factory workers using heavy machinery can reduce crush injuries or pinch hazards with advanced notice of shaking. This is not an exhaustive list, but rather a snapshot of the critical lifelines and industries that could benefit from early warning.

EEW is not a panacea, nor a replacement for robust infrastructure or seismic retrofits. EEW is a tool that augments risk mitigation efforts both before and after a rupture. The benefits clearly outweigh the costs. Three lives saved, two semiconductor plants warned, one BART train slowed, a 1% reduction in nonfatal injuries, a 0.25% avoidance in gas-related fire damage, could each in theory save enough money to pay for one year of operation of the system for the entire U.S. West Coast. EEW could also reduce the number of injuries in earthquakes by more than 50%.

These specific examples represent just the beginning of what will be a much longer list of possible applications for EEW. As EEW technology becomes better known and understood, as EEW system are further implemented around the world, and as our world becomes ever more interconnected and automated, more and more businesses will be able to identify appropriate applications to safeguard their own assets. It therefore seems clear that the savings substantially outweigh the costs of implementing EEW.

DATA AND RESOURCES

The video of the early warning alert can be found at https://www.youtube.com/watch?v=f3zGvs_hjdo (last accessed February 2016). The semiconductor companies in California listing can be found at http://semiconductorcompanies.com (last accessed March 2015). Airbus A318 listing can be found at http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/new-airbus-aircraft-list-prices-for-2015/ (last accessed April 2015).

ACKNOWLEDGMENTS

This work was funded by the Gordon and Betty Moore Foundation through Grant Number GBMF3024 to University of California, Berkeley, and the U.S. Geological Survey (USGS)/ National Earthquake Hazards Reduction Program Award G12AC20348. The authors would also like to thank Kevin Copley at Bay Area Rapid Transit (BART), John McKnight of The Salvation Army, and Margaret Vinci at Caltech for their insight.

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Published Online 23 March 2016