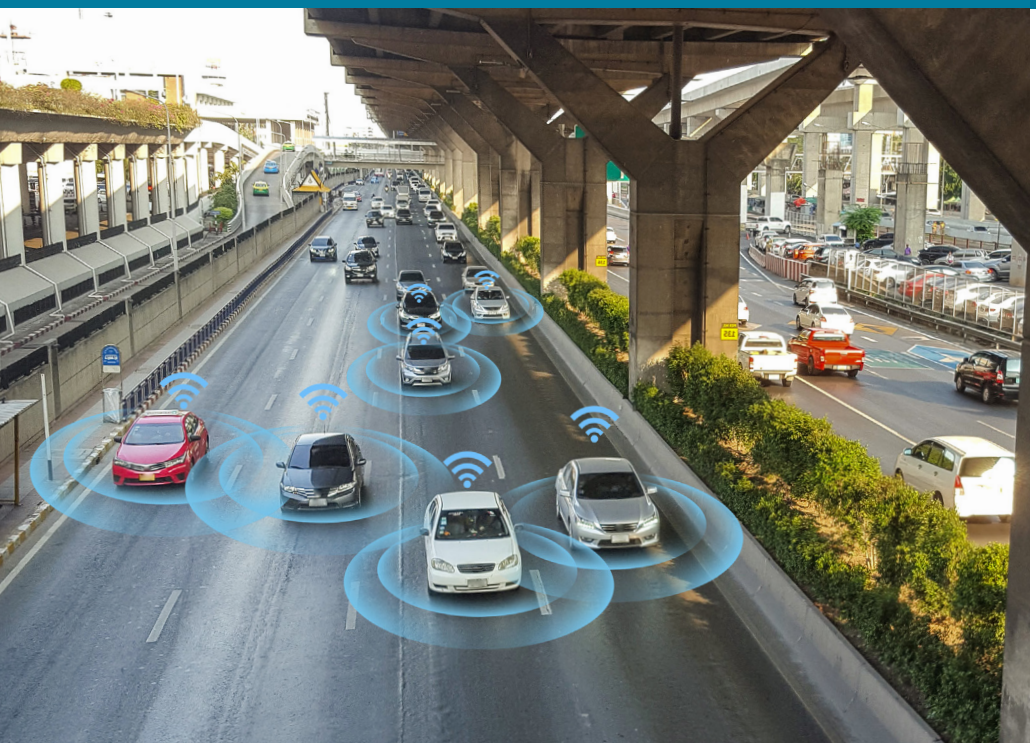


Accessing the Fast and Furious Pace of Autonomy to Transform Mining

EXECUTIVE SUMMARY

The benefits from achieving autonomous mining operations are significant, ranging from improving health and safety by removing people from hazardous environments, to improving productivity, reducing costs, and improving levels of mineral resource recovery. The ultimate opportunity is to totally reimagine the design and operation of a mine. Therefore, It is no surprise that the mining sector, along with defense, was an early mover in autonomy. However, despite nearly 15 years of development, less than 3% of mobile equipment in mining is autonomous. While there have been some successes, the results to date indicate that industry has lacked consistent leadership on autonomy development.

With solutions sourced from mining OEMs, the industry has largely been deprived of the innovations resulting from investments in the wider autonomy space which have played out over the past three years, and are expected to continue into the foreseeable future. These mining OEM autonomy solutions were architected through proprietary building blocks over time and developed as closed and proprietary systems. The history of technology development has demonstrated that systems designed by and for specific hardware platform suppliers are expensive, provide limited interoperability, lead to vendor lock-in, and constrains innovation.

Seeking to create “flow” in the mining process by moving from batch to continuous, open and interoperable systems allow for technology developers to benefit from advancements achieved in other sectors, and accelerate and future proof their own innovation efforts. The desired future world of a fully autonomous mine is achievable only when all mobile equipment can act autonomously and collaboratively. This necessitates, at a minimum, that the respective OEM systems are interoperable and are based upon standards so they can communicate and easily work together in an economic manner.

Learnings and experience from other industries tell us that the transition from a closed and proprietary system to a more open and interoperable system is very difficult—nearly impossible, from a technical and business model perspective. Moreover, the mining market, with fragmented efforts across both the miners and supply base, is relatively small in contrast with the automotive world.

We recommend a path forward for the mining industry to create a solution based on an open and interoperable standard. Also concentrate various diffused efforts to send a signal to the market that mining is a viable opportunity and offers a path to a much bigger market of controlled industrial environments.

The Autonomy Landscape: Fast and Furious

There is a relentless pursuit of innovation and a furious pace of market activity in the autonomous vehicle space. The technological enablers, business drivers, and investment environment have come together to create a race for the future of transport and mobility.

In the past two years, four main clusters of activity have emerged with increasing reliance on the technology sector, including startups, to provide breakthrough innovation, resulting in a web of connections across the clusters.

1. OEMs building optionality through multiple bets

The number of OEMs and industrial companies pursuing autonomy on their own is a small and declining number. To build optionality they are resorting to acquisitions, partnerships, and joint ventures to share the cost and risk of development, thereby acknowledging the intense competition from technology and mobility services providers.

Large industry incumbents have recently announced significant joint ventures and partnerships. In February 2019, **Ford and VW** announced that they will combine their efforts in autonomy with a new company (jointly owned) centered around Argo AI, with VW providing US$600 million in equity. The JV will have US$1.1 billion in working capital and will house the IP of its autonomous platform.

"It's my opinion that you can't do this alone."

- Jim Hackett, CEO, Ford
Wall Street Journal, Jan. 15, 2019

German-based automotive manufacturers **BMW and Daimler** have also unveiled a joint venture covering new-generation services such as driverless vehicles, ride-hailing, and pay-per-use cars. In March 2019, Daimler acquired a majority stake in Torc Robotics, an autonomous trucking startup.

2. OEMs and auto suppliers working with the technology sector and startups

OEMs and automotive suppliers are looking to combine the innovation velocity, speed, and nimbleness of startups with their scale and expertise. However, the competitive landscape for OEMs and industrial companies is significant with very high stakes. Many have surrendered their independent autonomy development efforts and have acquired, invested in, or partnered with the vast pool of startups.

GM's $1 billion acquisition of Cruise Automation in 2016, and Aptiv/Delphi's $450 million acquisition of nuTonomy are recent examples. Delphi has split into two companies, and is housing the new emerging autonomy space into Aptiv, where the nuTonomy acquisition was merged into. This is a trend of combining startup speed and technology with automotive domain knowledge. Another example of this is Ford's $1 billion stake in Argo AI in 2017. Argo has since added Softbank as an investor and is now a subsidiary of Ford and newly merged with VW's autonomy efforts.

3. The technology giants

Companies such as **Google (Waymo), Uber, Tesla, Baidu,** and **Amazon** represent examples of technology giants. They combine deep pockets with the tech-savvy characteristics of startups. They are relentless forces in every sphere they compete in, including autonomy. Amazon entered the autonomy space publicly in February 2019, with US $1 billion in investments into Aurora and electric pick up truck/SUV maker Rivian. Waymo is arguably the leader in autonomy today. In April 2019, ahead of Uber's IPO, Toyota, Denso, and Softbank combined to invest US $1 billion in Uber's self driving division ATG, valuing it at US $7.25 billion.

4. Technology startups

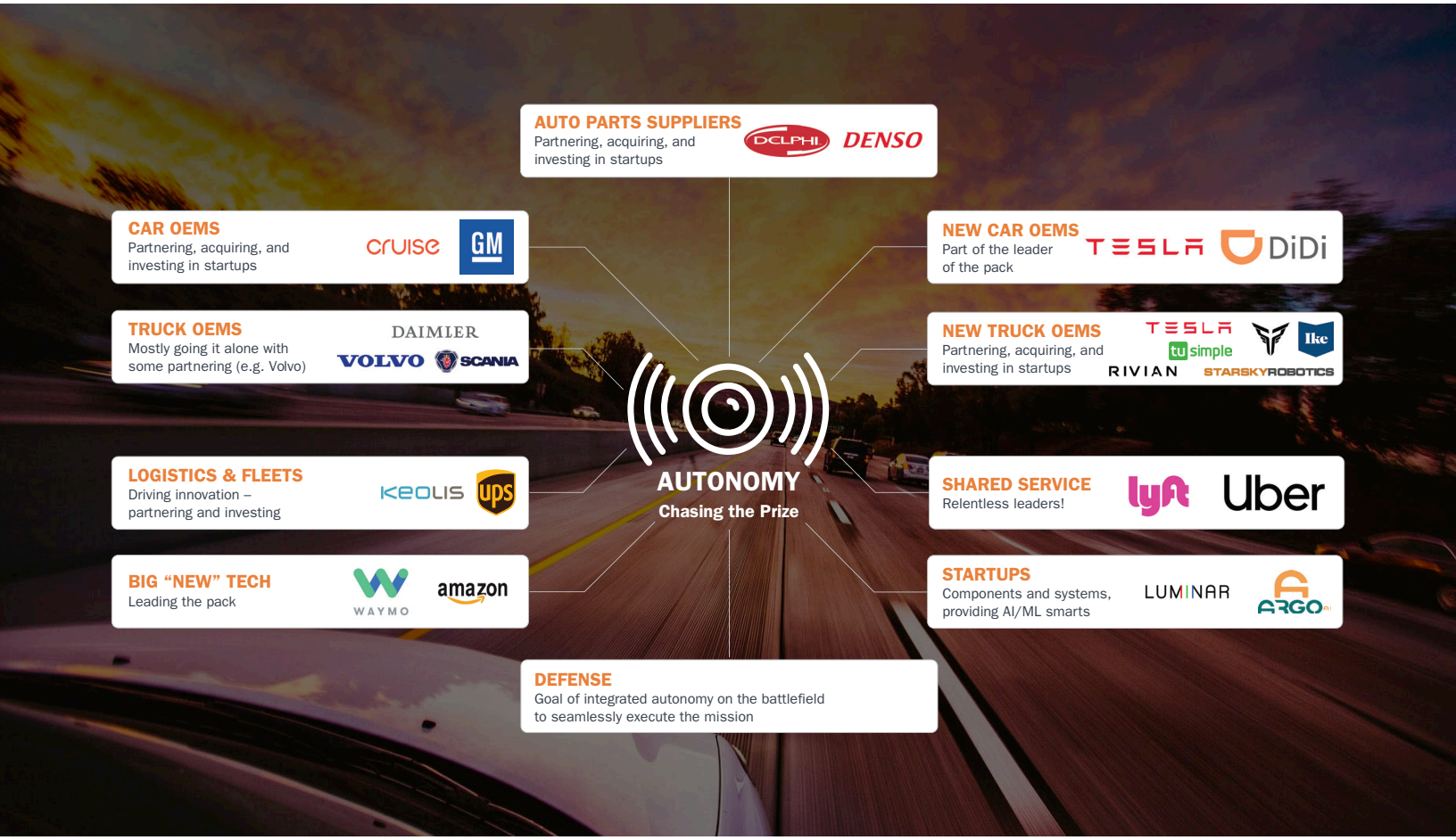
The universe of technology and autonomy startups is rapidly growing, turbocharged by billions of dollars of venture funding from VCs and corporates. **Softbank**, through its US$100 billion Vision Fund, is investing in artificial intelligence and machine learning, and their scope includes autonomy startups. Softbank recently invested US $940 million in driverless delivery startup Nuro, valuing it at US$2.7 billion. Nuro has a partnership with Kroger to deliver groceries. Self-driving car startup Aurora announced recently that it has raised more than US$530 million in funding, from investors including Amazon, Sequoia, and Shell.

Rather than manufacturing its own vehicles, Aurora is working with incumbents like VW and Hyundai, as well as Byton in China, to develop self-driving cars.

These tech startups aim to become the OEM's software platform of choice in a given area and/or dominate a market segment such as last mile delivery and shuttles in constrained environments.

"Traditional carmakers . . . fear that software will replace physical machinery as the most valuable components in vehicles."

- Financial Times, March 19, 2019



2019 has seen several emerging market and technology trends that are relevant to mining and broader controlled industrial environments that will accelerate capability development and market adoption.

Key Market Trend: Commercial Truck and Fleet Autonomy

There is a growing recognition, as indicated by levels of investment, that commercial trucks and fleets may represent more of a near term market for autonomy than passenger cars.

Large trucking fleet owners like **UPS** are being driven to autonomy by severe driver shortages (estimated to be as high as 90,000 per year by the American Trucking Association) driver health, safety, and fleet utilization. The NHTSA estimated over 4,300 fatalities in 2015 due to truck related crashes. The US National Safety Council estimates that 40,200 people died in accidents involving all motor vehicle deaths in 2016, a 6% rise from the year before. This comes after a 7% increase in 2015, which implies a 14% increase over a two year period, the largest such increase in more than half a century. Increased miles driven and distracted driving are believed to be the two main underlying reasons for this.

Startups Ike and TuSimple are examples of autonomous trucking and fleet startups.

Ike, a self-driving truck startup which achieved Series A funding in February 2019, claims to be taking a systems engineering approach and sprinkling in a little Silicon Valley agility. Ike isn't focused just on quickly building out integrating self-driving software and sensors to get on the road. Rather, it is working on determining the design and architecture first. The focus is on an entire system that accounts for everything in the self-driving truck, from its wire harnesses, alternator, and steering

column to durable sensors designed for the highway, computer vision, and deep learning that allows it to see and understand its environment and make the proper decisions based on that information. That systems approach also includes proper validation before testing on public roads.

TuSimple, a Sino-US company that launched a few years ago, hit Unicorn status in February 2019, and is planning to scale up its commercial autonomous fleet to more than 50 trucks by June 2019. It is currently testing on a 120-mile highway stretch between Tucson and Phoenix in Arizona, as well as in Shanghai. Truck manufacturing suppliers are working with TuSimple on the integration of autonomous software with powertrain, braking. and steering systems. It has developed a camera centric perception solution for high-speed trucking, which it claims has vision range of up to 1,000 meters, a significant improvement over LiDAR's 250 meters (optimal quality at 150 meters). TuSimple's camera, combined with software algorithms, enables the system to track distance, relative speed, and vehicle type of various objects spotted while on the road, and has an intention prediction feature that allows the vehicle to understand what those objects might do. This equips the vehicle to accomplish a number of complicated tasks, including anticipating congestion ahead and making a lane change in a smooth, uninterrupted movement — no disc braking necessary.

Key Technology Trend: Exponential Learning

Many of the VCs investing in autonomy have a view that algorithm advances and learning will accelerate dramatically from the more linear progression of the past. In fact, the rate of learning could hit that exponential curve and this will further accelerate innovation and breakthroughs in artificial intelligence and machine learning. This trend is exemplified by the emergence of deep learning simulation engines from Cognata and Waymo, through its soon-to-be open sourced platform.

Key Technology Trend: The Dash to the Edge

It is becoming apparent that the more self contained a vehicle is, i.e., "on the edge," or able to operate safely without V2X communications, the better for overall productivity and safety. Startups like Xnor.ai, Brodmann17, Deepscale, and Helm.ai are trying to address this issue through their software. A big win is that "on the edge" networks and communications can run on commoditized and cheap hardware, saving costs when scaled for vast industrial applications.

Key Technology Trend: The War for the Platform/ Operating System of Choice

Technologically, autonomy is still the "wild west" with really no operating systems or standards emerging as clear winners, and no dominant players. Competing players can be divided into three groups:

- **The Leaders:** These are companies who have had a head start in technology development, such as Waymo (who has licensed its technology to Chrysler), GM/ Cruise, Ford/Argo, Uber, Tesla, and Baidu/Apollo
- **The Challengers:** These are well-funded companies that have the ability to compete over the longer term, and examples include Aurora, Nuro (which has licensed its technology to Ike, the autonomous truck OEM), Zook, and Pony.ai.
- **The Chip Guys:** These companies understand the technology platforms game, and have a legacy of prior success. Examples include Qualcomm, Nvidia, and Intel/Mobileye.

The Current State of Autonomy within Mining and Other Controlled Industrial Environments

Controlled industrial environments offer an opportunity for autonomy solution providers to scale up, de-risk, and prove their technology. They could act as test beds of high scale, relatively lower regulation and in a more controlled environment.

One example is **Volvo CE** and its partnership with a customer, Skanska, in a test site to create the world's first emission-free quarry. Drawing on the electromobility and automation expertise of the Volvo Group, the research project, called Electric Site, aims to electrify each transport stage in a quarry, from excavation, to primary crushing and transport, to secondary crushing. This effort included, as a concept machine, eight small prototype HX2 autonomous, battery-electric load carriers to transport the material from the primary mobile crusher up to the secondary static crusher.

Another example is one of the major container terminals at Long Beach in California. It is one of only a handful of fully autonomous and electric container terminals in the world. It includes 57 stacking and ship to shore cranes and 58 ground vehicles. To attain the full safety and productivity benefits offered by autonomy, the port found it had to step back to rethink and redesign the physical space, the flow of work and processes.

The opportunity for controlled industrial environments is very broad, ranging from mining, forestry, ports, and agriculture, to construction.

Autonomy in Mining

The levers for value creation in mining, where autonomy can play a critical role are significant.

HEALTH AND SAFETY

- Improve health and safety by removing people from hazardous enviroments
- Make work more interesting and engaging with people able to focus on the higher value work and less repetitive work

PRODUCTIVITY

- Improve fleet utilization
- Radical improvement in production outputs
- Take a manufacturing approach to mining
- Minimize downtime

COST REDUCTION

- Optimize material movement equipment size to match the ore body and mine design
- Save costs related to technology, operations, and utilization

RESOURCE RECOVERY

- Improve levels of mineral resource recovery
- Target mineral resources currently not feasible technologically or economically
- Reimagine the mining process

The mining industry, along with defense sector, was an early mover in autonomy. However, despite 15 years of OEM led development, and the apparently strong case for autonomy, less than 3% of mobile equipment in the entire industry is autonomous. The adoption rate of autonomous haulage for open pit mining is accelerating with larger deployments by **Rio Tinto** and **FMG** and big moves from the likes of **BHP** and **Teck Resources**. Acceleration is also occuring underground (e.g. Resolute Mining), where arguably the value proposition is greater, as well as in autonomous drilling and use of teleremote.

Rio Tinto is clearly the autonomy leader in mining and the most advanced toward realizing the vision of a fully autonomous mine. Rio Tinto has a significant autonomous haulage fleet; autonomous drills and trains. It has partnered with the University of Sydney to develop the Mine Automation System (MAS), a way to mitigate the disadvantages of the closed OEM systems. Rio Tinto has developed an OEM agnostic autonomy solution on top of MAS, for drilling equipment, which is now deployed across multiple OEM drills.

"Fully integrated and highly automated from resource to market by 2025"

—Andrew Mackenzie, BHP CEO, Bank of America Merrill Lynch Global Metals, Mining and Steel Conference, May 15, 2018

Nevertheless, the mining industry has lacked consistent leadership on autonomy development. With solutions sourced from mining OEMs, the industry has been deprived of the innovations resulting from investments in the wider autonomy space that have played out over the past three years and are expected to continue into the foreseeable future.

The major mining OEM autonomy systems were architected and developed as closed and proprietary systems. Learnings and experience from other industries tell us that such systems are very difficult to transition to a more open and interoperable system, nearly impossible, from a technical and business model perspective.

The implications of such closed and proprietary systems are significant.

1. They tend to be expensive to develop and deploy, which results in lower adoption rates and keeps unit costs high.
2. They are very expensive to maintain, and this reinforces their high costs. Charge out costs are high and impact production.
3. It is very difficult, or may require enormous expense to absorb and apply new emerging technologies that provide new capabilities.
4. As a result of the above factors and the pace of external innovation, these closed solutions continually fall behind in functionality. They are simply unable to keep up with the pace of technological innovation.

5. Customers of closed and proprietary based systems are continually locked out from massively improved functionality and significantly improved economics, and may not have an achievable financial or technical migration path to a new system.

One mining executive surmised that the current state is an absolute impediment to a true autonomous mine that covers all mobile equipment, as it is extremely difficult to integrate all OEM systems and the closed proprietary system inherently locks out innovation.

These factors create an environment with high barriers for new entrants, and a vicious cycle of slowing down the pace of innovation to that dictated by mining OEMs. Customers risk being locked out of innovations achieved in other sectors, and the reinforcing cycle only makes this worse in the future. In fact, we believe that in the curent state it will be nigh impossible technically and economically to move to a fully autonomous mine where all mobile equipment is autonomous and working together. This requires a series of agreed standards that ultimately results in an open and interoperable platform.

Despite the efforts of various bodies like **GMG** and **AMIRA**, universal standards have not emerged. Wenco announced in April 2019 that it is advancing Hitachi Construction Machinery's (HCM) vision of an open and interoperable ecosystem of partners for autonomous mining, and that it is anchored in ISO standards. This is a market signal recognizing the implications of the current state of closed and proprietary systems.

The broader mining industry has typically sought solutions from traditional OEM suppliers. However, the autonomy market and landscape and the enormous size of the prize could offer new approaches.

- **Optionality through partnerships:** Car OEMs and mobility service providers are pursuing multiple paths for autonomous technology. The mining industry could learn from them and build optionality into its autonomy strategy, so that mining could benefit from the relentless innovation cycle that is producing massive results in functionality and price reduction.
- The industry needs to pursue a more **open approach** that provides an accelerated path to new technology innovation.
- The current investment and M&A environment is creating a huge **war for talent** in autonomy, and the big technology companies are well positioned to win. **Partnering will become a necessary path** to the future to ensure the mining industry is in the flow of innovation, allow it to influence the future innovation agenda, and tap into the talent that it may otherwise find difficult to access.
- **Mining platform for autonomy:** Companies like Nvidia are creating development and test/simulation tools to make autonomy development easier. However, this will take time to mature.

This then creates a priority for an open and interoperable approach.

Approaches to Open and Interoperable Standards

An open and interoperable technology system is one whose interfaces are completely understood to work with other products or systems, at present or in the future, in either implementation or access, without restrictions. They enable a plug and play approach, and are often based upon a standard. Open and interoperable systems allow for technology developers to benefit from advancements achieved in other sectors, and accelerate and future proof their own innovation efforts. When such systems are based on a standard, it refers to an established norm or requirement, usually a formal document that establishes uniform engineering or technical

"The history of the computer industry has shown that open systems provide:"

- **Easy integration** of best of breed (i.e. plug and play)
- **Easiest way** to build scale
- **Higher rates** of adoption
- **Higher number** of providers
- **Least expensive** to develop and buy
- **Higher levels** of adaptability

– **Bill Visnic**, *Autonomous Vehicle Engineering*, October 2018
Clareo analysis

criteria, methods, processes, and practices. The standard becomes an approach for collaboration between multiple stakeholders that typically represent the demand (user) or supply side (vendor), or both.

While we focus on the notion of open and interoperable technology systems, there are myriad of related terms, which can get confusing as they are sometimes used interchangeably. These terms include standards, platforms, operating systems, and APIs. The notion of open and interoperable itself is not black and white, as we have a pathway to transition from a closed and proprietary system, using APIs, to an at least somewhat open and interoperable from a customer perspective. Hence, we try to avoid jargon and labeling and focus on desired outcomes instead.

Technology that allows for easy and affordable interoperability and plug and play has several advantages:

1. Drives innovation
2. Lowers the barriers to entry for new providers
3. Lowers the cost of development and maintenance
4. Dramatically lowers the cost to end users
5. Accelerates the rate of adoption
6. Allows users to more easily migrate to solutions (greater flexibility and less vendor lock-in)
7. Breaks the dominance of the few closed proprietary providers

Below are some case studies from other industries on how they have successfully adopted open and interoperable systems and standards.

Their approaches tend to be categorized into the following mechanisms: consortium based, standards based, and dominant technology provider. Each of these has a trade off between speed to standard vs. speed to adoption. The technology industry, which includes many autonomy companies, prefers the speed to adoption pathway as it drives value creation faster.

Enterprise Applications Industry

In the 1980s and early 1990s most enterprise applications were based upon closed and proprietary systems resulting in a limited set of providers; were expensive to develop; experienced difficulties in integrating disparate systems; were expensive to license and implement; and saw limited and slow adoption rates. Then in the 1990s and early 2000s, we saw the emergence of more open systems via open and interoperable platforms like **UNIX**; and finally the emergence of full open and interoperable platforms via the cloud (e.g. AWS) combined with an entirely new business model (Software as a Service). The result has been a collapse in barriers to entry for new developers (e.g., the cost to develop has declined 99%); huge reductions in cost to users, resulting in rapidly increasing adoption; ability to plug and play with multiple vendors and moving away from one vendor lock-in; and increased velocity of innovation. The winners have been users and entrepreneurs, and the losers have been monolithic vendors with closed proprietary systems and hardware companies.

"Renovo CEO Chris Heiser believes that just like the computer industry, automated-driving development will converge to the use of just a couple of standard operating-system platforms."

– SAE Automotive Vehicle Engineering, October 2018

Consortium Approach, Digital Standards Association: Ocean Carriers

In the container shipping industry, customers are leading the way for "digitization, standards, and interoperability." Five of the world's largest ocean carriers, **Maersk, CMA CGM, Hapag-Lloyd, MSC** and **One**, are creating an industry association to define common information technology standards that will be open and free for all industry stakeholders to use.

As digitization sweeps the market, industry leaders realize there is an urgent need for a neutral and non-profit body that would ensure interoperability through standardization. Though several of the five carriers in the association are competitors, all recognize that a common set of standards will enable all parties to concentrate on value adding differentiation, highlighting that collaboration will increase value and reduce risk. Rather, establishing a common IT standards and governance [will help] streamline and digitize the shipping process in a modern way.

"It's in the customers' and all stakeholders' best interest if container shipping companies operate with a common set of information technology standards. We are striving for less red tape and better transparency."

- André Simha, CIO, MSC, November 15, 2018

Telecom/Mobile Industry Standards

The telecom industry, specifically the mobile wireless sector, has seen several decades of evolution. While the applications and technologies from today look vastly different from the early days of 1G analog mobile service or 2G early digital services, and now on the cusp of 5G for ultrafast internet and multimedia services, the theme of industry collaboration through standards has remained constant. In the early days, these standards were driven by mobile service providers who wished to ensure equipment utilized in their networks worked with each other in a consistent manner, even though they were sourced from multiple vendors. This enabled the industry to grow, for example, by offering a consistent consumer experience and service through regional, nationwide, and eventually, international roaming. Currently, standards organizations are driven by the technology providers, who are often competing to have their technology or approach be accepted as part of a standard by all stakeholders, including service providers. This can translate into significant competitive advantage if competing technology providers have to play catch up or rework their products to be standards compliant.

Standards for Interoperability Approach: The USB Case Study

The USB drive interface exemplifies the idea of "plug and play" to connect peripheral devices. However, in the early '90s, there was no such ubiquitous port or device, creating complexity, confusion, and frustration among consumers and retailers. The industry recognized that something needed to change, so Intel stepped in to develop the Universal Serial Bus, or USB. Intel was uniquely prepared to tackle the problem because of its proximity and relationship with key stakeholders, including platform and device OEMs.

The Intel development team zeroed in on four factors for success for the new solution: (1) simplicity; (2) low production cost; (3) highly compatible; and (4) bringing on key supply and demand-side stakeholders.

"There was a recognition that companies didn't mind healthy competition around standardized technology because everybody comes out ahead, as the market grows and there is opportunity for innovation."

- Bala Cadambi, Former Intel General Manager, Memory and I/O Technologies

"Two Decades of Plug & Play: How USB Became the Most Successful Interface in the History of Computing," Intel Report

The Path to Openness and Interoperability in Mining

It's not just an act of faith; 50 years of technology has demonstrated that systems designed by and for specific hardware platform suppliers are expensive, provide limited interoperability, lead to vendor lock-in, and constrain innovation.

Insights from the autonomy landscape and case studies in open and interoperable systems that need to be considered are:

- Adoption is extremely slow for a pure standards-based approach without a product.
- A high concentration of major customers provides an opportunity for buyer-led initiatives for open and interoperable systems.
- A dominant technology provider tends to sweep the field after a chaotic and expensive race!
- Hardware companies don't do software well, and incumbent hardware companies invariably lose this race.
- During that chaotic race, multiple bets are placed across technology/partners. This results in co-opetition, with players collaborating and competing against each other to hedge against risks.
- This needs a very good understanding of the IP landscape, in order to identify areas of competitive advantage versus areas which should be made open to drive adoption.
- Business model innovation combined with a more open and interoperable technology approach leads to acceleration of adoption and the entry into the market of new players.

We believe that it may be more realistic to achieve full autonomy in underground mining sooner, and that the following scenarios may apply to open pit mining:

1. **Autonomous haulage only in open pit mining:** The mining industry is currently locked into vendor-specific autonomous haulage on certain model trucks, and this scenario could continue with some expansion.
2. **Partially autonomous open pit mining:** This could be comprised of teleremote shovels and autonomous haulage, and would include people driving lights vehicles.
3. **Fully autonomous open pit mining:** This is a high value opportunity and provides the ability to reimagine the mine. It requires pushing standards in common areas such as safety, and use of common language and terminology, to achieve interoperability and OEM agnostic open systems (APIs, language, safety).

The desired future world of a fully autonomous mine is achievable only when all mobile equipment can act autonomously and collaboratively. This necessitates, at a minimum, that the respective OEM systems are interoperable and are based upon standards so they can communicate and work together.

The most progressive miners understand that a fully autonomous mine delivers a transformational change in value - safety, mine redesign, reduced variability, productivity, and new approaches to mining, such as swarm mining. This requires a platform that is open, interoperable, and therefore OEM-agnostic. We face a small concentrated market within mining, with diffused efforts across both the miners and supply base, in contrast with the automotive world where companies with massive resources indicate they cannot do it alone! So the key question is — what is the path forward for the mining industry?

We recommend an approach that begins to concentrate various diffused efforts, which will send a signal to the market that mining is both viable and offers a path to all controlled environments. This will attract new players and venture capital into the market and accelerate a 'virtuous cycle' of innovation.

We have illustrated several successful paths to this state, and on balance we believe the most viable approach for mining is to form an industry consortium to drive the development of the platform and create a standard which allows for the development of multiple interoperable solutions.

- A supplier consortium is unlikely to form on its own, given competitive dynamics of dominant OEMs with closed proprietary systems.
- The only viable path to acceleration, therefore, is a buyer side consortium, which should include some of the major mining companies. This will help focus and concentrate otherwise diffused efforts of various miners, OEMs and other providers (eg. ASI, RTI).
- Initial success will encourage OEMs and other providers (e.g.; startups and companies from the fast and furious wider landscape of autonomy) to participate.

The potential challenges to achieving this include:

- Small market size not attractive to innovators; this can be addressed by creating solutions for controlled environments, not just mining
- Mining companies traditionally don't collaborate well
- Lack of technology startups and venture capital
- Procurement vs. partnering mindset
- Traditionally slow technology adoption
- Persistent under-investment in innovation

In addition, there is what we call the "safety trap", which is where the mining industry uses safety as a rationalization to (1) support a closed proprietary approach under the pretense that a single vendor solution is somehow safer; (2) safety must be designed in first, and that the rest of the autonomy world places a lower priority on safety.

What's Next? A Call to Action

The path ahead for autonomy in mining is unclear. More than a decade of investment has resulted in little to show. We have highlighted a path to achieve openness and interoperability, but the evolution from the current state may take numerous forms:

- A continuation of today's proprietary solutions, with a hope that this would eventually change over time.
- The fast and furious world of autonomy technology will enter the mining industry.
- The mining industry, through a coalition of the willing, including mining companies and OEMs, utilizes a collaborative approach to develop an open and interoperable standard.

For the industry to achieve this, it will take a **culture shift** and a **degree of boldness**. One venture capitalist posed that to achieve this degree of change will require a shock to the status quo. Even Jeff Bezos, the visionary CEO and founder of Amazon, thinks boldly about mining and reimagines mining as a fully autonomy operation.

"Mr. Bezos appears to have in mind something other than a trade-based interplanetary economy, however. His plans take for granted speedy technological progress of the sort that would enable large-scale mining and materials processing by autonomous robots."

– The Economist, March 2019

Glossary of Terms

- **Platform:** A technology or group of technologies as a base, upon which other applications, processes, and technologies are developed. They are typically combined with a business model for doing so, and results in the domination of a given market space.
- **Operating System:** System software that manages computer hardware and software resources and provides common services for computer program (Wikipedia)
- **Technical Standard:** An established norm or requirement in regard to technical systems. It is usually a formal document that establishes uniform engineering or technical criteria, methods, processes, and practices.
- **Interoperable:** A characteristic of a product or system, whose interfaces are completely understood, to work with other products or systems, at present or in the future, in either implementation or access, without any restrictions often based upon a standard. It is sometimes referred to as plug and play.
- **Open Source:** Software for which the source code is made freely available, and may be redistributed and modified.
- **API:** An application program interface (API) is a set of routines, protocols, and tools for building software applications. An API specifies how software components should interact.

ACKNOWLEDGEMENTS

The authors interviewed a number of executives from mining companies, automotive OEMs, technology companies and consortia, startups, venture capitalists, and private equity investors to seek multiple perspectives from organizations participating in the global autonomy ecosystem.

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About The World Innovation Network

Founded in 2003 at the Kellogg School of Management, The World Innovation Network (TWIN) is a global platform for collaboration between Kellogg School of Management faculty, corporate innovation leaders, non-profit organizations, and the government. TWIN's mission is to facilitate dialogues that promote innovation-led growth and build long-term prosperity for industries and society worldwide. Through events like TWIN Global, TWIN Dialogues, and TWIN Catalyst, TWIN is building a network of thought leaders who have the collective ability to advance the global prosperity agenda. Keynote speakers from past events include management theorists Gary Hamel and Phil Kotler, former U.S. Secretary of Defense Bill Perry, former Supreme Commander of NATO Admiral James Stavridis, former Kraft Co-CEO Betsy Holden (also a TWIN board member), Republic of Colombia President Juan Manuel Santos, and Abbott Labs CEO Miles White.

To find out more, visit **www.twinglobal.org**

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