Mining and Representing the Concept Space of Existing Ideas for Directed Ideation

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Design innovation projects often generate large numbers of design ideas from designers, users, and, increasingly, the crowd over the Internet. Such idea data are often used for selection and implementation but, in fact, can 1also be used as sources of inspiration for further idea generation. In particular, the elementary concepts that underlie the original ideas can be recombined to generate new ideas. But it is not a trivial task to retrieve concepts from raw lists of ideas and data sources in a manner that can stimulate or generate new ideas. A significant difficulty lies in the fact that idea data are often expressed in unstructured natural languages. This paper develops a methodology that uses natural language processing to extract key words as elementary concepts embedded in massive idea descriptions and represents the elementary concept space in a core–periphery structure to direct the recombination of elementary concepts into new ideas. We apply the methodology to mine and represent the concept space underlying massive crowdsourced ideas and use it to generate new ideas for future transportation system designs in a real public sector-sponsored project via humans and automated computer programs. Our analysis of the human and computer recombination processes and outcomes sheds light on future research directions for artificial intelligence in design ideation.
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1 Introduction

In design innovation projects, ideas can be generated from individual ideation, team ideation (such as brainstorming), and other intuitive and directed ideation methods [1]. Results from these approaches are typically viewed as the output of an ideation process or sprint. The results will then be further evaluated and selected for prototyping, user-testing, embodiment, detailed design, and implementation. In fact, such ideas arising from individual or collective human ideation and cognitive processes can themselves be used as sources of inspiration for generating new ideas. In particular, the generic elements of the original ideas, which we call elementary concepts, can be recombined to generate new ideas. We define a concept space of a collection of ideas as the set of elementary concepts whose combinations form these ideas. The co-occurrence frequency (i.e., combination frequency) of the concepts in an idea indicate their interrelatedness in the concept space. However, it is not a trivial task to extract elementary concepts from typically expressed idea data and represent them in a manner that can stimulate or generate new ideas. This difficulty is because idea data are often expressed in unstructured natural language, drawings, sketches, and digital form. For the research reported here, we focus on ideas represented in unstructured natural language.

In this paper, we develop a methodology which integrates natural language processing (NLP) and graph theory to mine the concept space underlying a massive unstructured idea dataset in a manner that can guide the recombination of the elementary concepts for new conceptual design ideas. The method extracts semantic units, mainly words, and their co-occurrence relations from original raw ideas to approximate the concept space and represents it in a core–periphery structure. The core–periphery structure representation is motivated by prior studies that suggest highly valuable designs are likely to contain both common and uncommon combinations of prior concepts [2], i.e., cover both the core and the periphery of the space of elementary concepts underlying prior

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ideas. In turn, the core–periphery structure representation of the concept space can be used for further design ideation by recombining elementary concepts into new ideas.

Figure 1 illustrates an example of elementary concept space and two approaches of concept recombination using the space as the basis of new design ideation. Here, the elementary concepts are the semantic units of the original idea descriptions, including verbs, nouns, adjectives, and adverbs. The nouns (e.g., transmitter, receiver, ball, car, etc.) mainly describe objects, and the verbs (e.g., travel, ride, work, etc.) mainly describe functions and activities. They are implementable, and it is easy to interpret them as concepts. Meanwhile, the adjectives and adverbs (e.g., efficient, small, anywhere, somewhere, etc.) are needs and descriptors, and also serve as conceptual elements of ideas. For simplicity, we call all of them the elementary concepts hereafter.

The first approach of elementary concept recombination focuses on *exploiting* the elementary concepts in the existing concept space and recombine them to form new ideas. For example, "small," ball," "travel," and "enough" are elementary concepts from different existing ideas, and thus their recombination may lead to a new idea. Given that the existing ideas are only a subset of the total potential combinations of the elementary concepts in the space, exploiting the recombination of the elementary concepts underlying them would generate many new ideas. The second approach involves the *exploration* of additional concepts outside the space and combines them with the elementary concepts within the space to form new ideas. For example, "efficient" and "rapid transit" within the space can be associated with the concepts "card like," "transmitter," and "receiver" to form a new idea. Human designers may start with the elementary concepts in the space for inspiration and associate them with broader concepts from their own knowledge or external sources to form new ideas. Therefore, the elementary concept space mined from a set of ideas can be used for generating new ideas, via the *exploitation* of elementary concepts within the existing space and the *exploration* of external concepts beyond the space for new combinations.

The proposed methodology is aimed to augment creative ideation and concept generation in the early phase of the design processes. We apply this methodology to mining and representing the concept space that underlies a large set of crowdsourced raw ideas on future transportation system designs for a public sector innovation project. Then, we use the concept space to stimulate humans and design computer ideation programs to generate new ideas via concept recombination. The analysis of the human-generated and computer-generated new ideas and the ideation processes provide directions and inspirations for the development of computer ideation methods and tools based on prior idea data.

2 Related Work

To mine the concept space of existing ideas for directed ideation, our methodology brings together natural language processing to extract elementary design concepts from unstructured idea description texts, network analysis to structurally represent the concept space, and combinational creativity theory to guide directed ideation. In the following, we briefly review the techniques and theory that we draw on in this study.

2.1 Natural Language Processing. Our method starts with the extraction of the elementary terms from massive unstructured idea description texts. In the field of NLP, there have been rule-based approaches, learning-based approaches, and hybrid approaches to named entity recognition (NER) and terminology extraction [3,4], generally followed by part-of-speech (POS) tagging, lemmatization, filtering, etc. NER and terminology extraction will be starting points for automatic text organization and semantic analytics of natural language data of design ideas, and the basic task for mining the concept space of unstructured idea description texts. In turn, the extracted terms can be further recombined to generate new ideas by humans or computer programs.

Natural language generation (NLG) is an NLP task of generating natural language from a machine-representation system such as a knowledge base. Simple NLG systems use a template without involving grammar rules, e.g., banks generate letters to consumers by inserting different personal information into the same template. More complex NLG uses language models to create texts dynamically and has been applied to speech recognition, machine translation, handwriting recognition, etc. A language model is inherently probabilistic [5]. The relative likelihoods of different phrases are useful for the applications that generate text as an output, e.g., to distinguish between words that sound similar in speech recognition by considering the previous words. Since a statistical language model is essentially trained on human-generated texts, it will generate texts similar to the original ones.

2.2 Core–Periphery Structure. Our method aims to represent the concept space as a network of terms, i.e., a semantic network. Network analysis has been increasingly adopted in engineering design research. For example, Fu et al. [6] built a Bayesian network on the semantic similarity of patent texts to visualize a network of patents based on their analogical distances. Lim et al. [7] applied structural network modeling to evaluate the interconnectivity of design ideas and visualized the networks to evaluate the diversity of solutions. Song et al. [8] recently adopted core–periphery structure analysis for finding the core and periphery

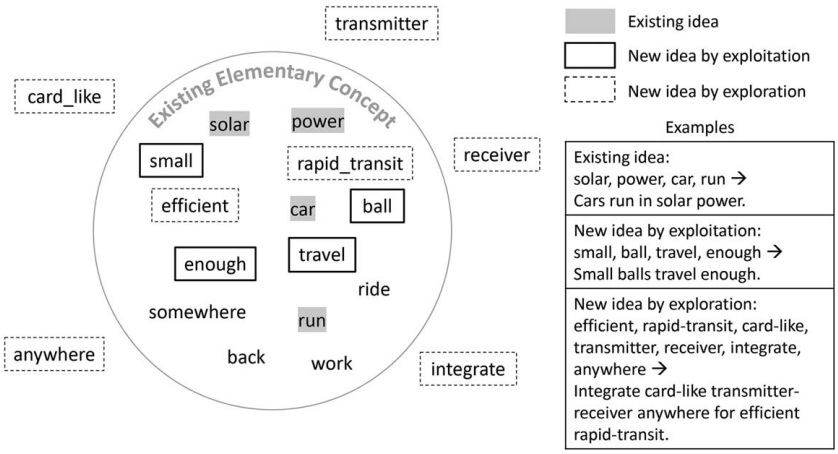
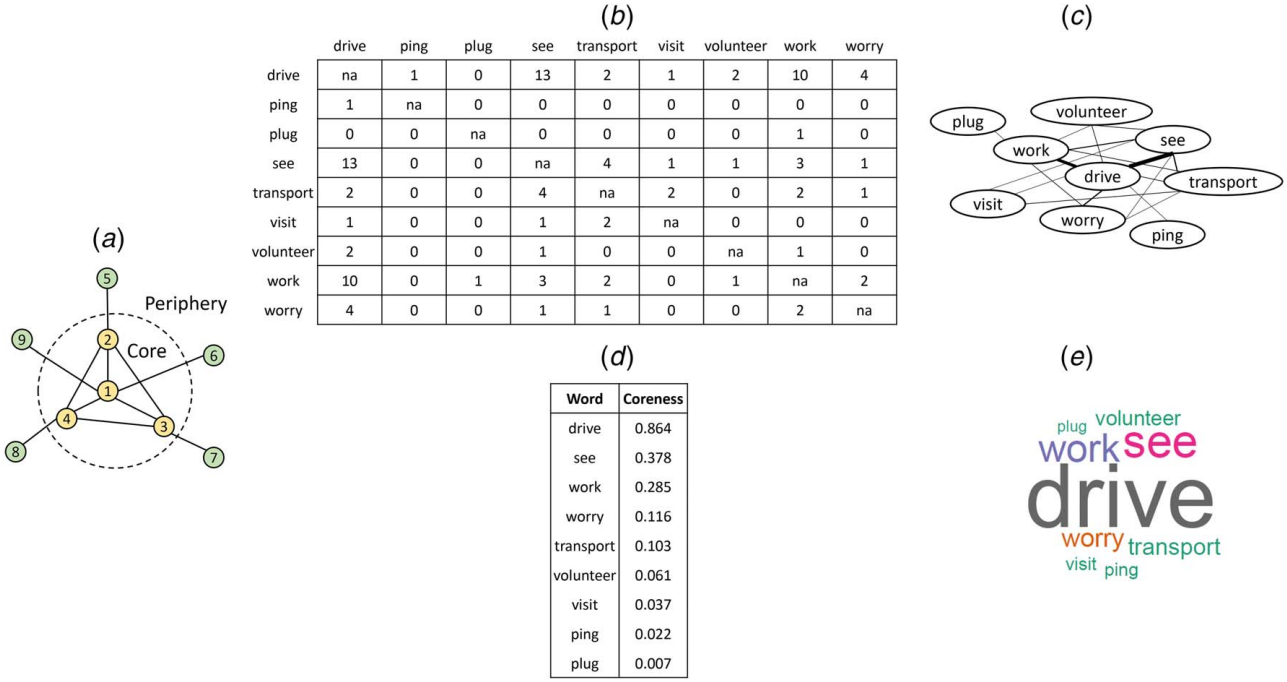


Fig. 1 Idea generation by the exploitation within and exploration beyond an existing concept space



(b)

	drive	ping	plug	see	transport	visit	volunteer	work	worry
drive	na	1	0	13	2	1	2	10	4
ping	1	na	0	0	0	0	0	0	0
plug	0	0	na	0	0	0	0	1	0
see	13	0	0	na	4	1	1	3	1
transport	2	0	0	4	na	2	0	2	1
visit	1	0	0	1	2	na	0	0	0
volunteer	2	0	0	1	0	0	na	1	0
work	10	0	1	3	2	0	1	na	2
worry	4	0	0	1	1	0	0	2	na

(d)

Word	Coreness
drive	0.864
see	0.378
work	0.285
worry	0.116
transport	0.103
volunteer	0.061
visit	0.037
ping	0.022
plug	0.007

Fig. 2 Core–periphery structure: (*a*) a network with an idealized core–periphery structure, (*b*) co-occurrence matrix of a corpus of verbs, (*c*) network representation of the verbs in (*b*), (*d*) coreness scores of the verbs in (*b*), and (*e*) word cloud visualization of the verbs in (*b*)

functions in a product family to guide the recombination of them for new product designs.

Our semantic network representation of the concept space emphasizes the core–periphery structure, which is embedded in many real-word networks, entails a dense core of cohesively connected vertices and a periphery of sparsely connected vertices [9,10], as illustrated in Fig. 2(*a*). Core–periphery structures in networks have been mainly studied using a discrete model (i.e., partition of the network in the core and periphery), and a continuous model (i.e., each node is assigned a measure of "coreness" to determine the degree to which it can be classified in the core). The core–periphery structure can differentiate the core (common) and periphery (novel) concepts in a concept space of ideas to guide the exploitation and exploration of the concept recombination for new ideas.

2.3 Combinational Creativity. The mined core–periphery semantic network of elementary concepts will serve as the basis for recombination of these prior concepts into new ideas. Inventions arise from the recombination of prior art [11–13]. Youn et al. [14] found that the recombination of existing technologies, rather than the introduction of wholly new technologies, has been the major driver of modern inventions. Fleming [15] found that novel combinations in patents give rise to both breakthrough and failure. Taura and Nagai [16] revealed that in idea generation via concept blending, the highest novelty is obtained from the base concepts with high distance. Design-by-analogy studies found that distant analogies contribute to novelty [17–19], but near-field analogies are more effective because of the ease of perception [20–22]. Venkataraman et al. [23] found knowledge distance between the solution concept and design problem increases the novelty of generated ideas but also decrease their quality. Fu et al. [24] posited that a moderate analogical distance is the most favorable for ideation outcomes.

Instead of assessing the novelty of singular combinations, several recent studies have investigated the complex space of multiple combinations of prior concepts or technologies that underline a new design. For instance, Uzzi et al. [25] found that the most cited scientific papers are grounded in a mass of exceptionally conventional combinations of prior work and a minor insertion of highly novel combinations. Kim et al. [26] and He and Luo [2] found that highly valuable inventions recombine both rarely and frequently combined technologies, based on patent data analyses. Taken together, these studies suggest the value of recombining the core/common and peripheral/novel concepts holistically in one for valuable new ideas.

2.4 Computational Approaches for Ideation. Many computer-aided ideation methods or tools have been developed. These efforts often curate design repositories, e.g., asknature.org and moreinspiration.com, which designers can search and retrieve prior art for design inspiration [27,28]. Murphy et al. [29] and Fu et al. [30] developed a vector space model for the analogical retrieval of the patent data to provide design stimulation. Siddharth and Chakrabarti [31] developed a web-based tool, Idea-Inspire 4.0, to support the search for analogical stimuli from a manually populated database of biological concepts and engineered concepts and represent them using function model, text, image, video, and audio. Mukherjea et al. [32] extracted biological terms and their semantic associations from biomedical patent abstracts to build the BioMedical Patent Semantic Web to support knowledge discovery in the specialized biomedical domain. Linsey et al. [33] used a WordTree to linguistically re-represent the design problems and help designers seek potential analogies for concept generation. Song and Luo [34] demonstrated how a network representation of the functions extracted from the patent data of a design domain can be used to aid designers in generating ideas of product variants and forming a product family. Luo et al. [35] presented how an interactive map of technology domains can be used to aid firms in exploring their future directions of design and innovation and to aid engineering designers in conceiving high-level design opportunities [36].

By contrast, our work in this paper is aimed to add to this growing strand of computer-aided ideation research by answering the following questions arising from data-driven ideation practices in engineering design.

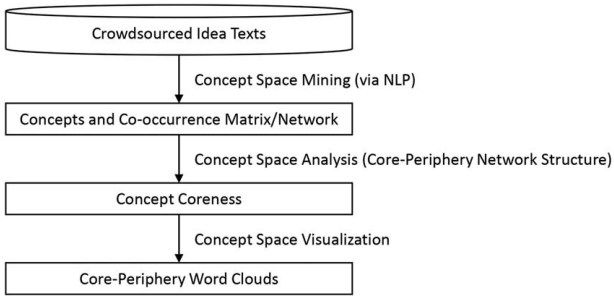


Fig. 3 The procedures to mine and represent the concept space of a set of ideas

- How can we extract the elementary concepts from massive natural language idea texts?
- How can we represent the concept space in a core–periphery structure?
- How can human designers and computers exploit and explore the new recombination using the structured concept space of existing ideas as the basis?

To answer these questions, we focus on mining and structuring the elementary concept space from the massive idea descriptions in unstructured natural languages for directed ideation uses. To do so, our methodology synthesizes NER from natural language processing, core–periphery structure analysis from network science, and combinational creativity theory from design science, as reviewed above. Note that, NER, core–periphery structure analysis, and combinational creativity theory were separately studied in different academic fields and have never been brought together for the interest of data-driven design ideation in the literature, to the best of our knowledge. Therefore, their synthesis gives rise to the novelty of the resulting methodology for directed ideation. In the following, we introduce our methodology in detail.

3 Method

In the following, we describe the methodology that combines NLP and network analysis to mine and represent the concept space of idea texts (Fig. 3).

3.1 Concept Space Retrieval (via Natural Language Processing). Keywords of different parts of speech are extracted by a sequence of NLP techniques (see the pseudo-code in Table 1 in the Appendix) to represent the elementary concepts embedded in the existing ideas. Noun keywords are extracted using TextRazor[2] which extracts all Named Entities (e.g., Car, Uber, and Manhattan) by leveraging a huge knowledge base of entity details from Wikipedia, DBPedia, and Wikidata. Its entity linking precision is the highest among alternative entity linkers [37]. Verbs, adjectives, and adverbs are extracted by the natural language toolkit (NLTK) [38]. The textualized ideas are tokenized and tagged as part-of-speech using NLTK's default Penn Treebank based tagger. Stop words are removed. Words were lemmatized to their base forms (e.g., cars to car) using NLTK's WordNet library. Then, typos and meaningless words were manually filtered. For example, the idea description—"We would ride hovercraft to a monorail station. The monorail would take us to work, school, etc."—would yield the keywords: ride, hovercraft, monorail, work. These keywords represent the elementary concepts of the idea on the surface.

Then, these keywords can be associated with one another based on their co-occurrences in different ideas, which indicate prior combinations. The keyword co-occurrence frequency is a reverse indicator of the novelty of the corresponding concept combination. Figure 2(*b*) demonstrates a concept co-occurrence matrix, in which the cell values are the numbers of co-occurrences of the pair of corresponding keywords of the column and row. For example, "drive" and "see" co-occurred in 13 ideas. In contrast, the combination of "drive" and "ping" occurred in one idea and is thus relatively more novel in this context. The co-occurrence matrix can be alternatively represented as a network, where the nodes are keywords and the link weights are pairwise co-occurring frequencies of keywords (Fig. 2(*c*)). By the definition of the link weights, the more connected concepts in the network would be more common (i.e., less novel) than the less connected ones.

3.2 Concept Space Analysis (Core–Periphery Network Structure). Then, we determine the coreness values of individual concepts according to their connectedness in the concept space, using the minimal residual method (MINRES) [39]. The method minimizes the following function F, which defines the discrepancy between the co-occurrence matrix R and the estimated relation matrix CC^T

$$F(R, C) = \sum_{i=1}^{n} \sum_{k=1}^{n} (r_{ik} - c_i c_k)^2, \; k \neq i \tag{1}$$

where C is a coreness column vector $(c_1, c_2, \ldots, c_n)^T$, R is the co-occurrence matrix, and r_{ik} is the co-occurrence frequency of keywords i and k in the same idea. To solve the equation, $F(R, C)$ is partially differentiated with respect to each element of C, and each equation is set to be equal to zero, resulting in the following equations:

$$c_i = \frac{\sum_{k=1}^{n} r_{ik} c_k}{\sum_{k=1}^{n} c_k^2}, \quad k \neq i \tag{2}$$

This set of equations shows that c_i, the coreness of keyword i, is a function of the coreness values of all keywords excluding i itself and the co-occurrence frequencies of keyword i with other keywords. MINRES assumes an initial estimated coreness vector C and uses an iterative process to update the C vector by substitution using Eq. (2). After C converges over iterations, the coreness values are normalized so that the sum of their squares is one. For example, Fig. 2(*d*) presents the coreness values of different keywords in the example co-occurrence matrix or network Fig. 2(*c*). In the example concept space, "Drive" is most likely to be in the core and "plug" is the most peripherical concept.

3.3 Concept Space Visualization (as Core–Periphery Word Clouds). The concept space underlying a collection of ideas is revealed as a set of keywords. The keywords indicate the elementary concepts whose combinations form the existing ideas, and their pairwise co-occurrence frequencies in the same idea indicate the novelty of their prior combinations. The co-occurrence matrix (e.g., Fig. 2(*b*)) and network (e.g., Fig. 2(*c*)) are straightforward visual representations of the concept space and can be sorted or structured to discern the relative core or peripherical concepts in the total space. However, when it comes to visual representation, they may become noisy and not informative when the space is large and complex. To visualize the space more intuitively, we represent the information in word clouds. Using the package *wordcloud* [40] in the *R* language,[3] words are assigned different sizes, colors, and positions in decreasing (or increasing) coreness so that the concept space exhibits a core–periphery structure. An example word cloud visualization based on coreness values is shown in Fig. 2(*e*). For general idea description data in natural languages, there will be a word cloud for each kind of keywords, including verbs, nouns, adjectives, and adverbs.

[2]https://www.textrazor.com

[3]http://www.r-project.org/

4 The Concept Space of Crowdsourced Ideas for "Future Transportation System Design"

We use the method above to reveal the concept space underlying one thousand ideas on future transportation system design from a crowdsourcing campaign that we ran on Amazon's Mechanical Turk. The campaign was part of a larger project with the Singapore public sector to generate ideas for future public transportation system designs. The design problem on Mechanical Turk was "Generate the next generation of public transportation for your region." 1000 crowdsourced ideas were collected and summarized for further ideation. Each idea is a descriptive sentence, paragraph, or narrative, e.g., "A more affordable public transit (or shuttle bus) that is crowdsourced/crowdfunded and takes passengers anywhere within a certain radius (e.g., 30-mile radius, etc.)." The idea description lengths range from 1 to 937 words. These crowdsourced ideas are massive, diverse, and messy in natural language. It is a major challenge for us to summarize these ideas and make sense of them as a holistic whole. We apply the NLP method above to process the idea descriptions in natural language and extract the keywords that represent elementary concepts underlying the crowdsourced ideas, including 704 nouns, 580 verbs, 710 adjectives, and 143 adverbs. On this basis, their co-occurrence frequencies in different ideas are derived to create the co-occurrence matrix and network, calculate the coreness of individual concepts, and create the core–periphery word clouds.

Figure 4 shows the distribution of words by coreness in different classes from the crowdsourced ideas. For all the word classes, the coreness distribution is steep, i.e., a large number of words have very low coreness while only a small number of words have high coreness. Figure 5 presents the word clouds generated on the coreness information of words. The word clouds are structured visual representation of the concept space underlying the massive crowdsourced ideas on future transportation systems design. The concepts in the core areas of the clouds are the common ones and provide a succinct summary of the massive crowdsourced ideas. They are not surprising and will not contribute to novelty in potential recombination for additional ideas. Meanwhile, the concepts in the periphery of the clouds are less common and may contribute to novelty if recombined into new ideas. Therefore, the core–periphery word clouds may provide holistic stimulation for new ideas that combine both common and novel concepts for a balance as suggested by the literature [2,26]. We further used the word clouds as aids for generating new ideas via concept recombination.

5 Concept Recombination for New Ideas

5.1 Human Recombination. We invited 58 researchers, including professors, postdoc fellows, graduate researchers, and designers at both MIT and SUTD to use the core–periphery word clouds (Fig. 5) as visual aids to generate new ideas to the same design problem on the future transportation system. Each participant was asked to select a word from each of four clouds of verbs, adjectives, nouns, and adverbs and then generate an idea that combines the concepts of the four selected words. Each participant was asked to submit once (a set of selected keywords and a generated complete idea), but two (2) participants submitted twice. Finally, we received 60 submissions (with two (2) participants contributing two ideas), but only 41 of the submissions are valid transportation-related ideas. Table 2 lists the 41 valid ideas and the four (4) words from different word clouds that inspired respective ideas.

We analyzed prior occurrences of the keyword/concept combinations of these new ideas in the original set of crowdsourced ideas. 95% of the valid ideas (except for Idea 2 and Idea 24) were new four-keyword combinations, where they represent three-keyword combinations at the same time, and 85% of these ideas (except for Ideas 1, 2, 13, 23, 24, and 37) present new two-keyword combinations. Therefore, the design ideation process, aided with

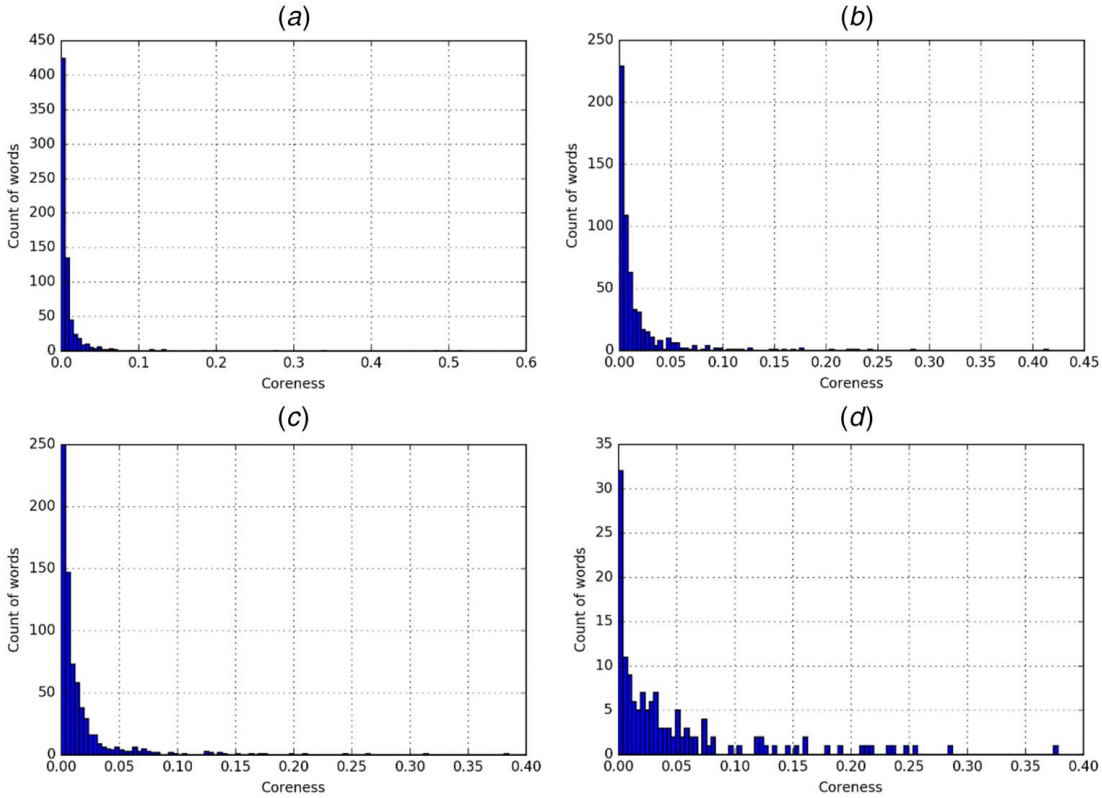


Fig. 4 Coreness distribution of words in different classes from the crowdsourced ideas: (*a*) noun, (*b*) verb, (*c*) adjective, and (*d*) adverb

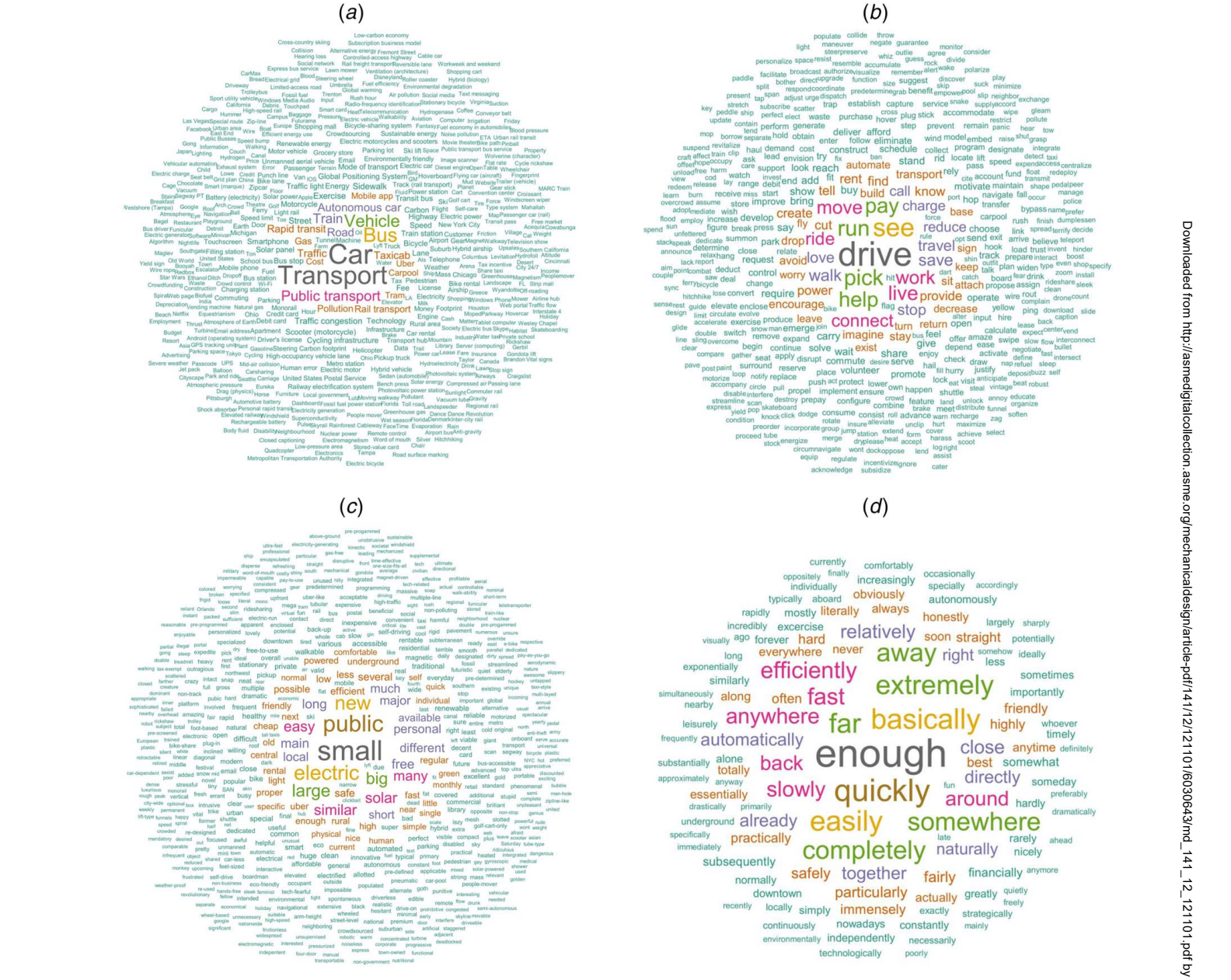


Fig. 5 Word clouds of different word classes from the crowdsourced ideas: (*a*) noun, (*b*) verb, (c) adjective, and (*d*) adverb

core–periphery concept space visualization from original crowdsourced ideas, leads to new ideas (as the recombination of prior concepts) in the total concept combination space defined by the original crowdsourced ideas.

Table 2 also lists the evaluation of the novelty, usefulness, and feasibility in three levels (high, medium, and low) for the ideas. These ideas were assessed by two engineering designers with extensive knowledge and experience in transportation. Their separate ratings have high Cohen's Kappa ratios (0.89 for novelty, 0.96 for usefulness, 0.93 for feasibility, and 0.93 for the pooled total). Only the assessments of three (3) ideas are different between two raters for novelty, one (1) idea for usefulness, and two (2) ideas for feasibility. The evaluations in Table 2 are based on their consensus. The ideas are sorted first by their novelty (from high to low), then usefulness, and then feasibility. Feasibility is emphasized by the public sector agency we worked with on this project. In working with a university, practitioners are typically more interested in exploring novel ideas. Thus, we prioritize novelty in sorting the ideas in the summary table.

Among the newly generated ideas, only Idea 1 was assessed as highly novel, useful, and feasible at the same time. Its novelty arises from leveraging of the electronic road pricing system (ERP)[4] of cars for transit systems by individuals and has been implemented in both Singapore and London. It can accelerate passenger flows in train stations because passengers need not tap cards at a counter to enter a platform; they are automatically identified and charged. Like Singapore's ERP that offers adaptive road fees, the system may adjust train or bus fees adaptively to re-route users along alternate public transit routes depending on loading and congestion, leading to adaptive public transit (either routing or fees). Therefore, this is a novel "low hanging fruit" that could impact passenger experience significantly.

Idea 3 is highly novel and imaginative and may have appeared in the *Harry Potter* movies. However, it is not directly feasible.

[4]https://www.lta.gov.sg/content/ltaweb/en/roads-and-motoring/managing-traffic-and-congestion/electronic-road-pricing-erp.html

A feasible alternative idea is to offer virtual reality (VR) travel experiences, i.e., VR teleportation, in telephone booths. Idea 4 is novel in that it explores the integration of social services and transport, i.e., bus and church together. It is feasible to have church sessions on a big bus with some custom layout designs. This general concept could be applied to integrating other social services in transport as well, such as counseling, exercise, etc., and redefine the future of transportation as a place where we do more than moving from place to place.

Idea 6 is quite novel although it is similar to or may be inspired by the Gyrosphere vehicle[5] that appeared in the movie *Jurassic World*. It is feasible but might be only useful for special places, e.g., parks, and occasions, e.g., disaster relief. This idea might also relate to or be inspired by the Goodyear Eagle 360 sphere tire concept that takes advantage of omnidirectional motion to revolutionize the way that cars drive with smoother and more complex dynamic motion. Idea 10 focuses on community-based sharing of vehicles of different functions, which have existed in city locations. It is useful and feasible. Idea 11 is the vision of many city governments and urban planners today. There have been some flying taxi projects (e.g., Uber Elevate) and also many initiatives to construct and use more tunnels (e.g., The Boring Company of Elon Musk) which contribute to a three-dimentional urban transportation system.

Idea 16 might be similar to or inspired by the Volkswagen Maglev Car concept, which looks like a bubble, released in 2017 in a public video. Its actual working would require a maglev infrastructure underneath the road surface. Idea 18 is related to the touted concept of flying taxi or the passenger drones. Some initiatives, such as eHang passenger drones in Dubai, AirBus flying taxi, and the Uber Elevate program, have been in pilot. Idea 20 might be useful for the disabled who have limited mobility. Idea 22 looks somewhat difficult and problematic to implement but actually was pursued by Ryanair some time ago.[6] One can imagine incentive schemes that incorporate health-mindedness into transportation.

Some of the ideas with low novelty have been implemented or prototyped in the real world. For instance, Idea 24 has been realized with car-sharing systems, such as ZipCar and Car2Go. Idea 27 has been fulfilled by the electric autonomous taxi fleet that Google and Uber are testing. The personal rapid transit (PRT) system in Masdar City[7] fulfills both ideas 24 and 27. Idea 28 is also useful and feasible and has been implemented by Lime Scooters and other electric scooter sharing services in the United States.[8] Idea 29 has been implemented by dockless bike-sharing systems, e.g., OFO and MoBike, from China. Idea 32 essentially is an electric, autonomous, and shared taxi. Grab has a large fleet of BYD all-electric taxies in Singapore.[9] Google, Uber, and NuTonomy have been testing electric and autonomous taxies in the U.S. and Singapore.

The foregoing discussions of the new ideas clearly demonstrate inspirations and directions for conceptual designs of future transportation systems. To better understand the ideation process and factors that may affect the effectiveness of this method, we gathered comments from the participants on their experiences of using the core–periphery word clouds as a rapid ideation aid. 43 of the 58 participants submitted feedback comments, and 38 comments were informative. The main points of learning from the feedback include

- Participants generally thought the ideation process aided by word combination was interesting, inspiring, and helpful. The word clouds stimulated them to conceive new combinatorial ideas that they would not have thought of before.
- The properties of word clouds, e.g., positions, word sizes, colors, scales, etc., affect users' attention for word selections.
- Some suggested reducing the number of words in each cloud, detecting phrases, categorizing words, etc.
- Some participants pointed out that they combine random words, while some others played around with the word they first noticed. There appear to be different patterns in the word selection process, which differ in fixation, flexibility, and randomness, in the word cloud aided cognition process.

These feedbacks suggested the possibilities to explore alternative and improve word cloud representations for ideation uses. A few findings from our own analysis of the new ideas are also noteworthy. First, we found that participants often transform selected words to different forms, e.g., connect → connection. Thus, it may be unnecessary to divide words into different groups by part of speech and let people select them in order, or, alternatively, provide different representations to designers, such as with the WordTree method [33]. Also, it is common to transform selected words to their "hypernyms," "hyponyms," and "synonyms," e.g., vehicle → car, imagine → brain controlled, etc. This type of transformation could be an effective way to expand the concept space and diverge in ideation since it could reach unlimited concepts outside the existing one. This could also be a strategy to alter a selected word and match up with the others. In addition, people may also use a portion of the selected terms or do not use them at all, e.g., rapid transit → rapid, electric-run → electricity.

Furthermore, it was common that the participants combined the presented concepts from the existing concept space with other external concepts to generate new ideas. The external concepts by nature are associated and retrieved from the participants' own knowledge. In such cases, the concept space visualization stimulated the human users to retrieve relevant knowledge from their own long-term memory according to some of the stimulating concepts, and to combine their own knowledge with the stimulating concepts to form new ideas. Such an ideation process integrating both exploitation and exploration is illustrated in Fig. 1.

5.2 Computer Recombination. The foregoing exercise encouraged humans to perceive, select, and recombine words from the clouds to develop new ideas. The prior knowledge of a person would condition one's ability and preference to perceive the relevance of certain concepts with the design problem and concept recombination. Using a computer to generate ideas to reduce subjective bias, or at least add to the combinatorial search, is a natural next trial. We developed a basic computer program to automatically pick and recombine concepts from the existing concept space to generate new ideas, without the constraints of a human on using the word clouds as visual stimuli.

In the interest of creative ideation rather than replication, we avoid the more popular statistical language models of NLG because they need to be trained on human-generated texts and are expected to generate texts similar to the original ones. Instead, we predefined a generic sentence template to avoid such convergence or fixation in creating natural language descriptions of new ideas. Alternative idea description templates can be drawn from models of conceptual design or extracted from human-generated idea descriptions. Some potential idea templates are shown in Tables 3 and 4 in the Appendix. To align with the forgoing human ideation exercise and avoid noise, our idea description template contains only one adjective, noun, verb, and adverb. Since adjectives must be bound with noun, and adverb must be bound with verb, there are two possible templates, i.e., "[adj] [noun] [verb] [adverb]" and "[verb] [adverb] [adj] [noun]." Indeed, the two templates can transform mutually. Because this design ideation approach was aimed for new artifacts (i.e., products, processes, systems, and services), we used "[adj] [noun] [verb] [adverb]" as the idea template. The computer program randomly selected one adjective, noun, verb, and adverb from the corresponding word clouds to fit the template

[5]http://www.jurassicworld.com/intel/location/gyrosphere
[6]https://www.independent.co.uk/travel/news-and-advice/ryanair-may-charge-a-fat-taxrsquo-for-its-overweight-passengers-1672979.html
[7]https://masdar.ae/en/masdar-city/the-city/mobility; https://www.youtube.com/watch?v=5G9X0voSi2Y
[8]http://fortune.com/2018/11/29/scooters-rental-startup-lime-definers
[9]https://cleantechnica.com/2017/02/24/byd-e6-selected-for-south-east-asias-largest-all-electric-taxi-fleet/

and generate a new idea. For example, if the computer selected "small," "ball," "travel," and "vertically," the generated idea would be "Small ball travel vertically."

We generated many random samples of 41 ideas using the computer. Pure random sampling gives an expected average coreness percentile at 50%. The computer-generated concept combinations appear to be highly novel and challenging for human designers to understand and interpret for feasible design. As an example, Table 5 in the Appendix presents the 41 ideas generated by the computer in one single round. The two transportation researchers who evaluated the 41 human-generated ideas with word clouds as visual aids also evaluated these 41 computer-generated ideas and found it challenging to make sense of them. This is not surprising that the unusual recombination of prior concepts will give rise to novelty in the new ideas but will also increase the variability and decrease the average quality of ideas.

To deal with the excessive variability of computer-generated ideas, in a further exercise, we sample the keywords with a coreness percentile range of top 10–50% in the word clouds for combinations. Since the coreness distribution is steep (Fig. 4), top 10–50% coreness refers to the semi-core of the core–periphery concept space. This higher coreness range in keyword selection was expected to yield the combinations of more common words that are easier to comprehend new ideas. Table 6 in the Appendix reports the keyword combinations from one single run. A novice participant in the previous human ideation and the two transportation researchers tried to make sense of these 41 computer-generated word combinations and succeeded 13, 17, and 41 times, respectively.

Figure 6 reports the comparison of the concept recombination in the three foregoing exercises. The computer program was run 100 rounds, with 41 ideas in each round to match the idea sample size in the human ideation exercise. As Fig. 4 shows, a greater number of new two-, three-, or four-keyword combos were generated in the computer recombination than in the human recombination (statistically significant with one-tail p-value <0.01, details in Tables 7 and 8 in the Appendix). This finding suggests that computer recombination mitigates design fixation for the exploitation in the same concept space for new recombination to yield new ideas [41]. More importantly, the results suggest that novel combinations of concepts across the design space may be created to augment and complement human designers. In particular, the computer combinations of keywords with controlled coreness percentiles in the top 10–50% have almost the same level of novelty (indicated by the count and percentages of new combos of words) of those based on pure random word selection, and meanwhile they are now more comprehensible for designers. This finding suggests a strategy to deriving novelty and comprehensibility of new ideas at the same time by increasing the coreness of the verbs, nouns, adjectives, and adverbs sampled from individual word clouds, while ensuring the combinations of them are novel.

6 Discussion

The human ideation exercise in this study shows that, by rapidly browsing a generated word cloud visualization of a concept space, humans can develop new combinatorial ideas that they would not have thought of before. The usefulness of the word clouds as ideation aids is demonstrated, although its layout design and use procedures require further investigation. In addition to the findings already discussed in Sec. 5, two findings are noteworthy. One is that there might be fixation early on with the first selected words. Second, despite the fixation in the concept space, humans naturally go beyond the given concept space and retrieve additional concepts from their own knowledge for combination with those from the given concept space to generate new ideas.

Computer-based random recombination enables wider and faster exploitation within the given concept space, augmenting and complementing ideation by human designers and providing new inspirations to be explored by designers. The randomness may lead to unusual combinations, which have higher novelty, but are also difficult to meaningfully interpret. A second computer-based recombination exercise in this study shows that increasing coreness of the keywords selected from the space might improve the comprehensibility of the resulting recombination, while still maintaining high idea novelty via novel combinations.

In this paper, the computer recombination was limited within the given concept space built on a specific dataset of prior ideas. In future work, a global knowledge database, such as ConceptNet and WikiData, and engineering design-focused knowledge database, such as the TKG—Technology Knowledge Graph [42–44], can be utilized to explore external concepts for combinations with the ones in the given concept space. Although humans do combine concepts beyond the given space as shown in the exercises of this study, the additional concepts focus on the individual human's own long-term memory and experiences rather than a global knowledge database. Furthermore, future extension work may adopt more sophisticated NLG techniques for easier-to-interpret idea descriptions, considering word embedding models to derive the semantic relationships between words. More sophisticated context-free grammar can also be considered to achieve both comprehensibility and variability.

Future development of computer-based design ideation methods and tools should harness the strengths of both computers (objective randomness and fast computation) and humans (imagination and natural language expression). The computer can sample concepts from the given space and exploit initial recombination tirelessly. Then, human ideation can focus more on expressiveness, adaptation, evaluation, interpretation, and out-of-the-space exploration, rather than word selection. Computer sampling may remind the human user of valuable combinations that humans might miss by browsing the word clouds. It may also drive the human user to relate the previously unrelated concepts and thus derive novelty. Meanwhile, the human user may still get fatigued after evaluating

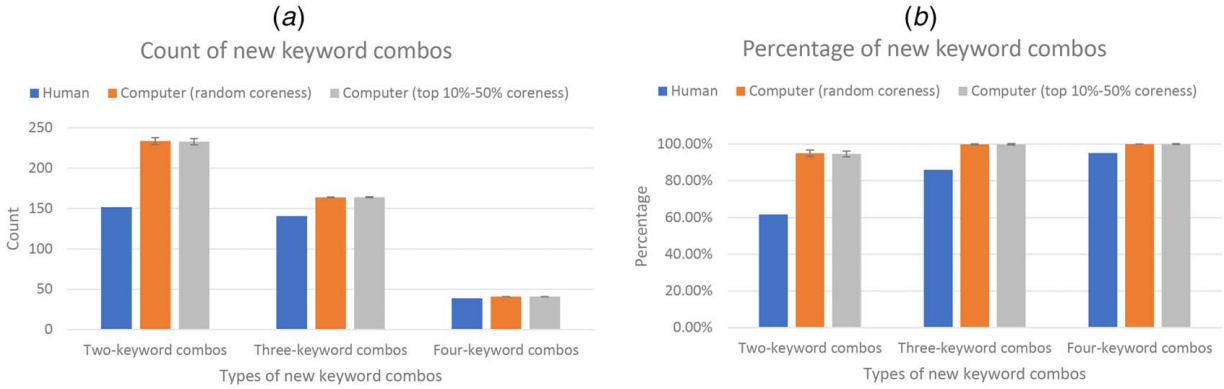


Fig. 6 Comparison of new keyword combos among different ideation methods. Error bars of one standard deviation are drawn.

and interpreting some word combinations generated by the computer, as indicated at the bottom of Table 6 and from the feedback of the participants. To reduce the cognitive loads of the human to make sense of computer-generated ideas, the recombination of words more in the cores might help as shown in our second computer exercise. Future work should develop intelligent algorithms for machine learning of the human user's latent preferences in real time as they evaluate and select computer-generated ideas. For example, it may make humans more productive if the computer programs can keep a portion of the presented words they use on the way, learn and match their language habits in the process, adjust the coreness of words for sampling, and so on.

These exercises have shed light on the exploitation–exploration manners of concept recombination for new idea generation using a given concept space of existing ideas as the basis, which are consistent with a Darwinian perspective to creativity—Campbell's blind-variation and selective retention model of creativity [11,45]. The given concept space is like a gene pool, and the elementary concepts are like genes. Exploitation refers to the variation of concept combinations among the existing concepts (like genetic recombination), while exploration refers to that involving external concepts (like gene mutation, complementary effect, plus genetic recombination). Newly generated ideas are like "new organisms" emerging from further ideation. Whether a new generated idea is meaningful, useful, and feasible depends on how well the elementary concepts adapt to each other and the context as a whole. The retention principle of ideas was assumed to be related to the coreness of their elementary concepts, inspired by prior studies on combinational creativity. The concept space evolves at the same time as the new ideas are generated. Thus, computers are better at blind-variation than selective-retention, while humans are the opposite.

Therefore, this paper suggests future research to develop computer-aided design ideation systems which integrate both intelligent algorithms and human ideation (Fig. 7). Such a design ideation system will enable both exploitation and exploration of concept combinations within and beyond the given concept space. Such a system, if successful, should ensure the quality of generated ideas in addition to the quantity and novelty. In the long term, given the advances in computation technologies and artificial intelligence, we anticipate the development of artificial intelligence systems that can generate many more and more novel ideas with satisfactory quality at the same time without human intervention, and thus enhance creativity in design.

7 Conclusion

This paper presents a new methodology to process design idea data in unstructured natural language to reveal the underlying concept space and represent it in a core–periphery structure for further ideation. In turn, the revealed concept space, in the form of core–periphery word clouds embedding co-occurrence information, can be further used as design stimuli to generate additional ideas and explore the design space. In contrast, traditionally, the ideas generated from human processes (e.g., individual ideation, group brainstorming, crowdsourcing, etc.) are typically not fully explored or comprehensively utilized as the source of inspiration for further design ideation. The proposed methodology fills this gap through a novel synthesis of NER, core–periphery network analysis, and combinational creativity theory from previously separate fields of research.

We apply the methodology to a real-world design innovation project on future transportation system design, where the approach generates many more novel, useful, and feasible ideas from previously crowdsourced ideas. Particularly, we use the revealed concept space as the basis for both exploiting and exploring concept recombination into new ideas, by humans and computers. The case study suggests the potential of our data-driven methodology to augment creative design ideation in the early phase of design processes.

It is important to note that, despite the use of crowdsourced design ideas in the present paper, the concept space can be also constructed based on other types of textual data that may contain design concepts for directed ideation uses. Such data forms may include technical reports, patent documents, academic papers, web articles, in-person brainstorming and ideation notes, and so on. That is, the proposed methodology and the foregoing discussion are not limited to the crowdsourcing context but have wide applicability.

In this study, basic NLP and complex network analysis techniques have been used to derive the structured concept space. Future work may focus on developing more advanced NLP and

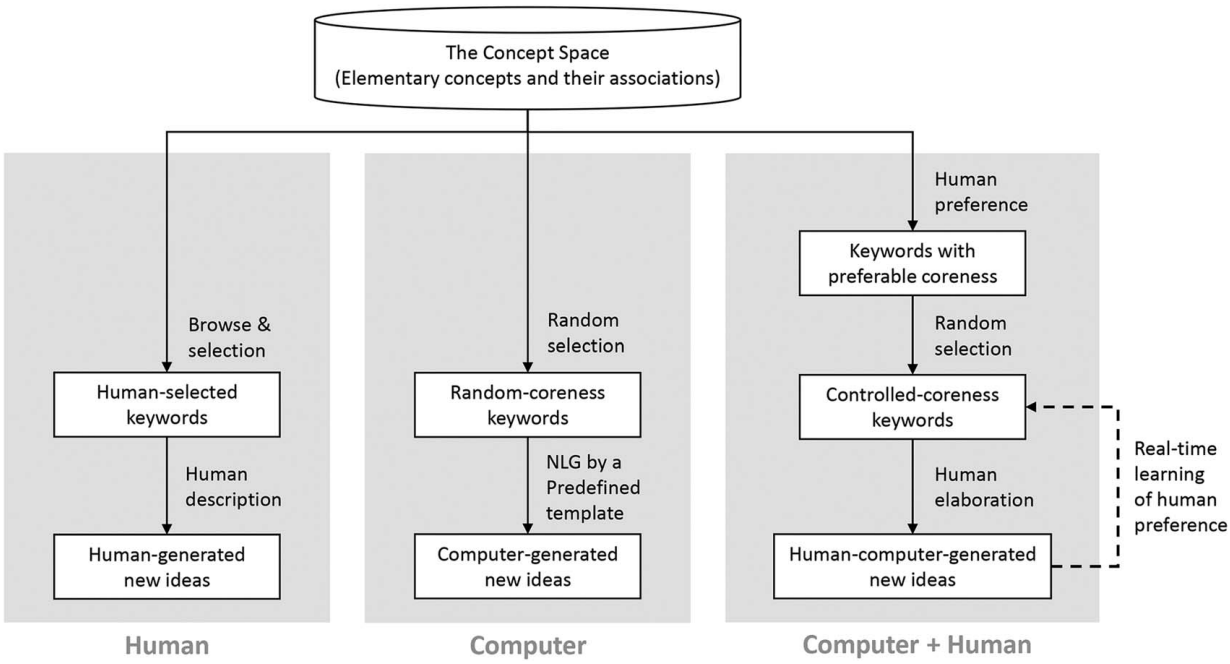


Fig. 7 Different approaches to exploit and explore concept combinations for new ideas

NLG methods to analyze and represent an engineering (or other knowledge domain) ontology database to enable computer-based exploration beyond the given space, as well as developing machine learning algorithms to learn human user's preferences. In sum, this research is a step in the journey to develop machine-learning techniques and computer-aided ideation systems or artificial intelligence for concept generation in engineering design.

Acknowledgment

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Appendix

Table 1 The pseudo-code that describes the algorithm to extract the keywords from massive idea descriptions

```
INPUT ideaList
DEFINE nounSet = { }, verbSet = { }, adjectiveSet = { }, adverbSet = { }
FOR idea in ideaList
   namedEntities = call API of TextRazor to extract Named Entities in idea
   nounSet = nounSet + namedEntities
   wordList = tokenize and tag different part-of-speech in idea
   wordList_cleaned = remove stop words in wordList
   wordList_lemmatized = lemmatize wordList_cleaned
   verbSet = verbSet + verbs in wordList_lemmatized
   adjectiveSet = adjectiveSet + adjectives in wordList_lemmatized
   adverbSet = adverbSet + adverbs in wordList_lemmatized
END
OUTPUT nounSet, verbSet, adjectiveSet, adverbSet
```

Table 2 Valid ideas generated using word clouds as human ideation aids

#	Verb	Adj	Noun	Adv	Human-generated ideas	Novel	Useful	Feasible
1	save	efficient	rapid transit	somewhere	Save time spent in the counters of rapid transit systems in peak hours by integrating a system such as ERP of Singapore with card-like transmitter-receiver in commuter-side and transmitters–receivers covering whole station entrance in station-side	High	High	High
2	drive	small	car	enough	Make a big car into smaller units that are only suited for 1 person, so people can drive or connect to others so there will be enough space in the street	High	High	Medium
3	teleport	universal	public transport	continuously	A continuously-operating teleportation "phone booths" in corners of streets. These booths can take you anywhere you want and operate with something like a bus card. Now the whole world is connected!	High	High	Low
4	love	big	bus	fun	A big bus is decorated like a church to communicate love	High	Medium	High
5	encourage	simple	walkability	anywhere	A shared transportation system like bus or taxi to offer an easy option that includes exploration. This was once called a "Sunday drive" a colloquial term for moving around solely to observe new places. It should be easy to adapt this route and make stops for fun	High	Medium	High
6	envision	futuristic	ball	incredibly	I envision a futuristic hamster ball vehicle that has incredible resistance to disasters	High	Medium	High
7	attach	soap	coffee	leisurely	The transportation in the neighborhood will be of leisure style with daily consumption experiences such as soap trials, coffee trials, and other service attachments	High	Medium	High
8	suspend	golf-cart-only	windows media audio	along	Suspended golf carts that travel along windows! Suspended window roads (so they are see-through and like the second layer of the road) that only golf carts travel along. Its a priority lane for golf carts, but its gotta be seenthrough so you can not carry dangerous goods inside. Semiautonomous golf carts that keep you in suspense as you look out your windows at them whizzing dangerously by	High	Medium	Low
9	happen	solar	street	already	Flash mobs on existing streets convert them to solar power plants inaccessible to cars	High	Low	Low
10	anticipate	various	spiral	fast	Have a set of vehicles for a neighborhood that	Medium	High	High

Table 2 *Continued*

#	Verb	Adj	Noun	Adv	Human-generated ideas	Novel	Useful	Feasible
					only the families in the neighbourhood can access. Different types like car, truck, van, motorcycle. And the families can use them as needed			
11	fly	underground	air pollution	anywhere	In the future, we could make the best use of the 3D space we leave to avoid congestion. The roads can be built anywhere in the air and underground. In the air, commuters wear customized suits to fly anywhere, while the underground tunnels are built deeper and more complex	Medium	High	Medium
12	fly	personalized	hybrid vehicle	anywhere	A flying vehicle that can be adapted to different individuals and different conditions	Medium	High	Low
13	travel	public	transport	enough	Share all the transportation at a reasonable price.	Medium	High	Low
14	fly	uber	train	anywhere	An Uber train that can fly anywhere	Medium	High	Low
15	hover	small	train	fast	Hover fast small train	Medium	Medium	Medium
16	drive	bubble	maglev	forever	Bubble maglev	Medium	Medium	Medium
17	load	mega	scooter	sharply	The new transportation system would be a convoy of scooters. You can hop on at any point and select your route. The scooters could automatically take you and your friends there, all at once. This would require a rail or something similar for scooters only	Medium	Medium	Medium
18	jump	monkey	coffee	exponentially	Vehicles carry passengers travel between rooftops of buildings, like monkeys jumping between (coffee) trees. The speed of traveling increases exponentially with the distance—so it will not take long to get anywhere	Medium	Medium	Medium
19	bypass	natural	speed limit	completely	So we need traversable wormholes	Medium	Medium	Low
20	imagine	easy	vehicle	fast	Brain-controlled car	Medium	Medium	Low
21	light	environmental	UAV	safely	Take environmental UAV to go safely with light speed	Medium	Medium	Low
22	snow	fat	tax	basically	Tax fat people for being fat, basically	Medium	Low	Low
23	move	efficient	transport	easily	Improve public transportation service so everyone could benefit. Encourage sharing between community members. Better urban design (e.g., cluster functional buildings based on the common needs of the community) to reduce the needs for transportation	Low	High	High
24	pay	electric	car	enough	There are enough cars in our world now. To reduce electric consumption, we could pay the car by usage	Low	High	High
25	automate	preprogrammed	trolleybus	autonomously	Offer a few bus lines using preprogrammed autonomous trolleybuses	Low	High	High
26	embed	viable	urban rail transit	sharply	Embed urban rail underground to link suburbs with cities	Low	High	High
27	automate	electric	autonomous car	constantly	The next generation of car would be automated, electric and runs constantly across the neighborhood	Low	High	High
28	connect	electric	rapid transit	anywhere	Last-mile rapid connection by using electric powered mobility rental devices	Low	High	High
29	assume	heavy	bike rental	friendly	More bikes for transport	Low	High	High
30	ride	easy	vehicle	anywhere	Vehicles that users ride on, easily used, easily accessible, and can be used anywhere	Low	High	Low
31	prevent	personal	drag (physics)	human error	Prevent personal physical human error automatically	Low	High	Medium
32	automate	smart	autonomous car	automatically	An autonomous car automates our transportation automatically	Low	High	Medium
33	power	high-traffic	share taxi	safely	Every share taxi will be renewable power charged at various stations where there is high traffic flow so that demand for share taxis can be supplied for. The taxis should be autonomous though, I am not sure if that makes things safer	Low	High	Medium
34	restrict	general	transport	underground	Create an underground infrastructure for vehicles and reduce surface traffic	Low	High	Medium
35	buzz	brilliant	blood pressure	technologically	technology bracelet that buzzes periodically to prompt you to be mindful in your busy day and measures your blood pressure too to alert you when you are stressed	Low	Medium	High
36	ping	public	couch	along	A couch where people can ping for services?	Low	Medium	High
37	drive	public	car	basically	Basically, we use public car more than a private one	Low	Medium	High

Table 2 *Continued*

#	Verb	Adj	Noun	Adv	Human-generated ideas	Novel	Useful	Feasible
38	encourage	free	autonomous car	efficiently	The next generation of transportation would be autonomous, free way to go, and encourage the efficiency of society	Low	Medium	Medium
39	share	solar	public transport	technologically	Apply solar on public transport	Low	Medium	Low
40	populate	free	train	efficiently	Train is the most popular and efficient way to transport and is free	Low	Medium	Low
41	see	electric-run	road surface making	already	Running track that can store electricity based on people running on it	Low	Low	High

Table 3 Potential idea templates defined from models of conceptual design

No.	Models of conceptual design	Potential idea templates
1	*Property mapping*: map a common property or feature to an existing concept (Taura and Nagai [16]), e.g., snow + tomato → white tomato	— [adj] [n] — [n] like [n] that can [v] [adv]
2	*Concept blending*: inherit partial properties from both the two base concepts (Taura and Nagai [16]), e.g., snow + tomato → powdered ketchup.	— [adj] and [adj] [n] — [n] that like [n] and [n]
3	*Concept integration in thematic relation*: integrate thematic scenes (situations, roles, etc.) of the base concepts (Taura and Nagai [16]), e.g., snow + tomato → humidifying refrigerator	— [n] in an environment like where [n] is — [n] plays a role as [n] does — [n] [v] [adv] as [n] does
4	*Variables of the design process*: artefact types, inspiration sources, experience adjectives, design attributes, media types [46], e.g., Design {an artifact} inspired by {primitive(s)} that is {adjective(s)} through {attribute(s)} using {a medium}	Design [n] inspired by [n] that is [adj] through [n] using [n]

Table 4 Potential idea templates extracted from human-generated idea descriptions

Manually extract idea templates from the submitted 41 relevant idea descriptions:
(1) Map the word stimuli to the related elements in a new idea.
(2) Replace the mapped elements with part-of-speech (i.e., [v], [adj], [n], [adv]).
(3) Generalize and simplify the sentence structure to obtain a short idea template.

#	Verb	Adj	Noun	Adv	Human-generated idea descriptions (elements mapped with word stimuli are marked by underlines: 1) from verb stimuli: single straight underlines; 2) from adj stimuli: double straight underlines; 3) from noun stimuli: single wavy underlines; 4) from adv stimuli: double wavy underlines))	Potential idea templates (1 verb, 1 adj, 1 noun, 1 adv)
1	save	efficient	rapid transit	somewhere	Save time spent in the counters of rapid transit systems in peak hours by integrating a system such as ERP of Singapore with card-like transmitter–receiver in commuter-side and transmitters–receivers covering whole station entrance in station-side	[v] for [adj] [n] [adv]
2	drive	small	car	enough	Make a big car into smaller units that are only suited for 1 person, so people can drive or connect to other so there will be enough space in the street	[adj] [n] to [v] [adv]
3	teleport	universal	public transport	continuously	A continuously-operating teleportation "phone booths" in corners of streets. These booths can take you anywhere you want and operate with something like a bus card. Now the whole world is connected!	[adj] [n] that can [v] [adv]
4	love	big	bus	fun	A big bus is decorated as a church to communicate love	[adj] [n] transformed to [v] [adv]
5	encourage	simple	walkability	anywhere	A shared transportation system like bus or taxi to offer an easy option that includes exploration. This was once called a "Sunday drive" a colloquial term for moving around solely to observe new places. It should be easy to adapt to this route and make stops for fun	[adj] system to [v] for [n] [adv]
6	envision	futuristic	ball	incredibly	I envision a futuristic hamster ball vehicle that has incredible resistance to disasters	[v] a [adj] [n] vehicle resisting disasters [adv]
7	attach	soap	coffee	leisurely	The transportation in the neighborhood will be of leisure style with daily consumption experiences such as soap trials, coffee trials, and other service attachments	[v] [adj] [n] to run transportation [adv]
8	suspend	golf-cart-only	windows media audio	along	Suspended golf carts that travel along windows! Suspended window roads (so they are see-through and like the second layer of road) that only golf carts travel along. It is a priority lane for golf carts, but it is gotta be see-through so you can not carry dangerous goods inside. Semi-autonomous golf carts that keep you in suspense as you look out your windows at them whizzing dangerously by	[v] [adj] vehicles traveling around [n] [adv]

Table 4 *Continued*

#	Verb	Adj	Noun	Adv	Human-generated idea descriptions (elements mapped with word stimuli are marked by underlines: 1) from verb stimuli: single straight underlines; 2) from adj stimuli: double straight underlines; 3) from noun stimuli: single wavy underlines; 4) from adv stimuli: double wavy underlines))	Potential idea templates (1 verb, 1 adj, 1 noun, 1 adv)
9	happen	solar	street	already	Flash mobs on existing streets convert them to solar power plants inaccessible to cars	convert [n] existing [adv] to something else [adj] and make it [v]
10	anticipate	various	spiral	fast	Have a set of vehicles for a neighborhood that only the families in the neighborhood can access. Different types like car, truck, van, motorcycle. And the families can use them as needed	[adj] vehicles like [n] that can [v] [adv]
11	fly	underground	air pollution	anywhere	In the future we could make the best use of the 3D space we leave to avoid congestion. The roads can be built anywhere in the air and underground. In the air, commuters wear customized suits to fly anywhere, while the underground tunnels are built deeper and more complex	Build roads in [n] and [adj] places. Help commuters [v] [adv]
12	fly	personalized	hybrid vehicle	anywhere	A flying vehicle that can be adapted to different individuals and different conditions	[n] that can [v]. It is [adj] and is operated [adv]
13	travel	public	transport	enough	Share all the transportation at a reasonable price.	Enable people to [v] [adv] by sharing [n] in a [adj] principle.
14	fly	uber	train	anywhere	An Uber train that can fly anywhere.	[adj] [n] that can [v] [adv]
15	hover	small	train	fast	Hover fast small train.	[v] [n] that is [adj] and works [adv].
16	drive	bubble	maglev	forever	Bubble maglev	[adj] [n] that people can [v] [adv]
17	load	mega	scooter	sharply	The new transportation system would be a convoy of scooters. You can hop on at any point and select your route. The scooters could automatically take you and your friends there, all at once. This would require a rail or something similar for scooters only	A convoy of [n] that enables people to [v] in [adj] places [adv]
18	jump	monkey	coffee	exponentially	Vehicles carry passengers travel between rooftops of buildings, like monkeys jumping between (coffee) trees. The speed of traveling increases exponentially with the distance—so it will not take long to get anywhere	Vehicles like [adj] things that can [v] between [n], with [adv] changing speed
19	bypass	natural	speed limit	completely	So we need traversable wormholes	[v] in a [adj] style without [n] [adv]
20	imagine	easy	vehicle	fast	Brain controlled car	[n] that people can [v] to operate. It is [adj] and works [adv]
21	light	environmental	uav	safely	Take environmental UAV to go safely with light speed	Take [adj] [n] to [v] and go [adv]
22	snow	fat	tax	basically	Tax fat people for being fat, basically	Ask [adj] people for [n] to [v] [adv]
23	move	efficient	transport	easily	Improve public transportation service so everyone could benefit. Encourage sharing between community members. Better urban design (e.g., cluster functional buildings based on the common needs of the community) to reduce the needs for transportation	Share [adj] [n] between community members to [v] [adv]
24	pay	electric	car	enough	There are enough cars in our world now. To reduce electric consumption, we could pay the car by usage	[v] [n] to reduce [adj] things [adv]
25	automate	pre-programmed	trolleybus	autonomously	Offer a few bus lines using pre-programmed autonomous trolleybuses	A few lines using [adj] [n] that [v] [adv]
26	embed	viable	urban rail transit	sharply	Embed urban rail underground to link suburbs with cities	[v] [n] to link suburbs with cities. Make it [adj] and work [adv]
27	automate	electric	autonomous car	constantly	The next generation of car would be automated, electric and runs constantly across the neighborhood	[adj] [n] that can [v] and runs [adv] across the neighborhood
28	connect	electric	rapid transit	anywhere	Last mile rapid connection by using electric powered mobility rental devices	[n] using [adj] devices to [v] [adv]
29	assume	heavy	bike rental	friendly	More bikes for transport	More [n] to make transport [adj] and [v] [adv]
30	ride	easy	vehicle	anywhere	Vehicle that users ride on, easily used, easily accessible and can be used anywhere	[adj] [n] that users can [v] [adv]
31	prevent	personal	drag (physics)	human error	Prevent personal physical human error automatically	[v] [adj] [n] [adv] and automatically
32	automate	smart	autonomous car	automatically	An autonomous car automates our transportation automatically	[adj] [n] that can [v] [adv]
33	power	high-traffic	share taxi	safely	Every share taxi will be renewable power charged at various stations where there is high traffic flow, so that demand for share taxis can be supplied for. The taxis should be autonomous though, I am not sure if that makes things safer	[n] will [v] sustainably and be supplied [adv], where there is [adj] flow

Table 4 *Continued*

#	Verb	Adj	Noun	Adv	Human-generated idea descriptions (elements mapped with word stimuli are marked by underlines: 1) from verb stimuli: single straight underlines; 2) from adj stimuli: double straight underlines; 3) from noun stimuli: single wavy underlines; 4) from adv stimuli: double wavy underlines))	Potential idea templates (1 verb, 1 adj, 1 noun, 1 adv)
34	restrict	general	transport	underground	Create an underground infrastructure for vehicles and reduce surface traffic	[v] [n] by creating [adj] things [adv] for vehicles
35	buzz	brilliant	blood pressure	technologically	Technology bracelet that buzzes periodically to prompt you to be mindful in your busy day and measures your blood pressure too to alert you when you are stressed	Something [adj] that can [v] [adv] to measure [n]
36	ping	public	couch	along	A couch where people can ping for services?	[n] where people can [v] for [adj] services [adv]
37	drive	public	car	basically	Basically, we use public car more than private one	[adv], we [v] [adj] [n] more
38	encourage	free	autonomous car	efficiently	The next generation of transportation would be autonomous, free way to go, and encourage the efficiency of society	Use [n] and [adj] roads. [v] the society to run [adv]
39	share	solar	public transport	technologically	Apply solar on public transport	Apply [adj] things on [n] to [v] [adv]
40	populate	free	train	efficiently	Train is the most popular and efficient way to transport and is free	[adj] [n] that works [adv] and can [v]
41	see	electric-run	road surface making	already	Running track that can store electricity based on people running on it	[n] that can store something [adj] based on how it [v] [adv]

Table 5 Pure random computer recombination in one round of ideation

#	Adj	Noun	Verb	Adv	Computer-generated ideas ("[adj] [noun] [verb] [adv]")
1	multi-layer	autotram	polarize	drastically	Multi-layer autotram polarizes drastically
2	sky	wire rope	alter	daily	Sky wire rope alters daily
3	exciting	wire rope	embed	visually	Exciting wire rope embeds visually
4	google	industry	lease	privately	Google industry leases privately
5	lit	evaporation	wipe	exponentially	Lit evaporation wipes exponentially
6	eco-friendly	disability	spread	outside	Eco-friendly disability spreads outside
7	electromagnetic	reforestation	harm	potentially	Electromagnetic reforestation harms potentially
8	steep	electric car	incentivize	specifically	Steep electric car incentivizes specifically
9	independent	exhaust system	store	mainly	Independent exhaust system stores mainly
10	successful	Canada	suffer	autonomously	Successful Canada suffers autonomously
11	hard	web portal	hurry	usually	Hard web portal hurries usually
12	goth	tire	transfer	sharply	Goth tire transfers sharply
13	fat	milk	enclose	visually	Fat milk encloses visually
14	capable	FL	draw	increasingly	Capable FL draws increasingly
15	future	aisle	anticipate	whoever	Future aisle anticipates whoever
16	rigid	park and ride	assume	exercise	Rigid park and ride assume exercise
17	military	vacuum tube	light	always	Military vacuum tube light always
18	awful	footwear	start	forever	Awful footwear starts forever
19	electricity-generating	wet season	say	typically	Electricity-generating wet season says typically
20	self-drive	altitude	facilitate	immensely	Self-drive altitude facilitates immensely
21	dedicated	auto-rickshaw	tie	often	Dedicated auto-rickshaw tie often
22	pickup	star wars	invest	less	Pickup star wars invest less
23	retail	inter-city rail	deal	always	Retail inter-city rail deal always
24	deadlocked	sedan (automobile)	lack	fairly	Deadlocked sedan (automobile) lacks fairly
25	northwest	transit pass	promote	obviously	Northwest transit pass promotes obviously
26	inner	toll road	purchase	fairly	Inner toll road purchases fairly
27	significant	elevator	charge	possibly	Significant elevator charge possibly
28	significant	ski	express	relatively	Significant ski expresses relatively
29	daily	rapid transit	refuel	daily	Daily rapid transit refuels daily
30	unpleasant	society	assign	close	Unpleasant society assigns close
31	phenomenal	Christmas tree	pedal	back	Phenomenal Christmas tree pedals back
32	spread	off-roading	hold	back	Spread off-roading holds back
33	bad	military vehicle	cod	around	Bad military vehicle cods around
34	critical	natural resource	avoid	already	Critical natural resource avoids already
35	expedite	airport	broadcast	anywhere	Expedite airport broadcasts anywhere
36	short	tax	predetermine	practically	Short tax predetermines practically
37	short	New Orleans	stand	often	Short new Orleans stands often
38	cycling-increased	Houston	pay	quietly	Cycling-increased Houston pays quietly
39	upfront	fruit	catch	basically	Upfront fruit catches basically
40	cab	school bus	rent	back	Cab school bus rents back
41	inexpensive	drag (physics)	run	practically	Inexpensive drag (physics) run practically

Table 6 Random computer recombination of keywords with top 10–50% coreness percentile in one run

#	Adj	Noun	Verb	Adv	New ideas with human sensemaking by a novice	New ideas with human sensemaking by a transportation Researcher A	New ideas with human sensemaking by a transportation researcher B
1	expedite	theatre	expect	exercise	Make each seat on the vehicle as an expedite theatre for the passenger, by wireless media recommendation, based on the passenger's facial expression, to refresh his/her mood and body	Design transportation modes that expedite the travel, meanwhile bringing theatre experiences or allow passengers to exercise in the vehicles	People jog or bike to work, an app integrates this activity with a dynamic multiplayer real-time theatre, so it is more engaging, that is you play a role and interact with other players on their commute
2	neighborhood	fossil fuel power station	lock	normally	None	Neighborhoods that use fossil fuel vehicles should be locked or isolated from the ones that use renewable energy vehicles	To facilitate electric vehicle usage, gas stations are made harder to use such as through requiring a permit to access them
3	automatic	Trenton	occupy	timely	The public transportation resources in a big city can be automatically distributed in surrounding small towns timely in holidays when people are on vacation	Automatically supply vehicles to fill the needs of passengers in different town areas timely	Cities, such as Trenton New Jersey are occupied through a control system. A large-scale system plans who will occupy what cities when according to a large-scale timing plan
4	unmanned	email address	ease	individually	None	Passengers can use email address as ID to access public transportation	A system to reduce the need to go to work, thus reduces transport load, an unmanned system automates many of our tasks. Rather than do everything we simply review the reports and edit individually as needed
5	total	Old World	disrupt	autonomously	None	None	To manage the growing complexity of transport, the new system, on the surface, looks like an archaic civilization, wagon cars, horses, and simple villages, with the advantage of modern technology, fusion, internet, AI hidden underneath
6	mega	ski lift	invest	nowadays	Invest more to build lifts in the regions where there are increasingly more elderly people nowadays	None	The city invests in a large-scale ski-lift to replace trains and cars. It will open much of the ground level for other uses
7	taxi	high-occupancy vehicle lane	haul	sometimes	None	Allow taxis to enter and use HOVLs when sometimes they are empty, in order to fully utilize the road space	This concept is known historically known as a carpooling lane. To extend the concept, new AI control systems will automatically force less crowded vehicles to the outer lanes, dynamically to optimize the ratio of people transported versus time
8	neat	telecommunication	configure	individually	I can use telecommunication to configure my autonomous vehicle and ask it to pick me up		Configure telecommunication systems individually, for instance, maybe I want to preprogram the system to download information faster in the mornings and I would pay more for that

Table 6 *Continued*

#	Adj	Noun	Verb	Adv	New ideas with human sensemaking by a novice	New ideas with human sensemaking by a transportation Researcher A	New ideas with human sensemaking by a transportation researcher B
9	car-less	Greece	enclose	downtown	None	Design policies for enclosed downtown areas to be car-less during certain times a day or a week given human traffic conditions	As an analogy to the island of Greece, cities are redesigned with higher quality architecture and gardens so that there is less "compulsion" to move from place to place it makes you happy where you are
10	solar-powered	iOS	prevent	totally	None	None	Using solar-powered modules, an IOS like system can prevent accidents where the road itself provides warnings when it detects cars about to have collision
11	applicable	walkway	activate	actually	None	None	Walkways are activated only when and where applicable. For instance, the lighting on the road would follow cars or pedestrians
12	box	flying car (aircraft)	wire	anytime	A plane is composed of modular box-like units based on the passenger number. Different units can communicate anytime	Box-like flying cars follow wires to move in the air	Flying cars are currently infeasible due to limited flight time—about 15 min. A network of wires would allow flying cars to be "tethered" to an energy grid that transmits power
13	designated	cart	lower	somewhat	None	None	There is designated cart that is lower power, for application such as goods transport which may have lower efficiency at high speeds
14	acceptable	rush hour	visit	everywhere	One can book an autonomous vehicle to visit anywhere at an acceptable price in rush hours	Design means to allow acceptable rush hour visits everywhere; this is a design goal indeed	Incentive schemes are put in place to motivate the movement of people to other places than just downtown during rush hour
15	narrow	convention center	notify	anytime	None	None	There are narrower roads in crowded areas. Second, users are notified when time is available to visit a certain place rather than guessing or blindly competition with other passengers/visitors
16	spontaneous	efficient energy use	benefit	always	Sustainable energy such as solar energy is always used efficiently and spontaneously and benefits the electronics passengers bring by wireless charging	The vehicles may intelligently respond to real-time traffic and driving conditions to adjust engines RPM for spontaneous opportunities of efficient energy uses	Vehicles coordinate road usage with spontaneous swarming or lane usage sharing, like runners drafting on each other to reduce energy usage
17	brilliant	Lowe	bypass	immensely	None	None	To enhance transportation city wide, bypass systems are designed using AI to optimize point to point commutations
18	advanced	shopping	shin	immensely	The advanced vehicle can send me to a shopping center which meets my shopping requirement and gives me immense recommendations	None	Rather than enhance transport, shopping is enhanced to a point that no one ever needs to transport for shopping which would immensely reduce transport requirements

Table 6 *Continued*

#	Adj	Noun	Verb	Adv	New ideas with human sensemaking by a novice	New ideas with human sensemaking by a transportation Researcher A	New ideas with human sensemaking by a transportation researcher B
19	neighboring	compressed air	hit	often	The vehicles can detect air quality and clear air when running	None	Cars to take advantage of compressed air to reduce aerodynamic friction caused by passing neighboring vehicles. A sort of compressed air shielding
20	integrated	hovercar	swipe	fairly	None	Integrated hovercar moves fast between straight-line points like swiping	Hovercars are unrealistic due to the high energy required to turn. Thus, a swipe or sweep-like road is developed. Imagine a luge track with hovercars, angles for tight turns
21	street-level	pollutant	bike	fairly	Bikes can filter pollutant on the street when used	None	To reduce pollutants, only bicycles are allowed on the street level. All motorized vehicles are restricted to below ground use where the air can be heavily filtered before returning to the surface
22	NYC	magnet	feel	essentially	None	None	To make maglev trains more appealing, develop a maglev train with the attractive hip-hop urban aesthetic of the NYC metro railway
23	renewable	navigation	dispatch	obviously	Ships use renewable energy, navigate and dispatch to the harbor autonomously	None	Use renewable energy to power dispatch systems and reduce the need for loading on other systems
24	future	sustainable energy	hover	somewhat	None	Future sustainable energy sources to power hover vehicles	Engage in research on hovering vehicles that use sustainable energy
25	stupid	carriage	send	obviously	None	None	Take an assumption that not all users have really considered an optimal destination. The system will help users to identify a more optimal destination that requires less travel. E.g. what is the nearest shoe store, is two blocks away rather than traveling to the center city
26	practical	sedan (automobile)	afford	anytime	None	None	Make a more practical and affordable alternative to ownership. Many ride-sharing systems are overpriced and exceed even the cost of car ownership. This is a problem that can be solved with better planning and control
27	stationary	wi-fi	capture	highly	Wi-fi is stable when flying high	Stationery wi-fi stations alongside roads in the city to capture vehicles that pass	Using a stationary wi-fi system, you can capture foot traffic from pedestrians that bump into each other. That is people cannot walk and use data anymore. Streetwalking will be more efficient as before cell phones
28	urban	public buses	eliminate	everywhere	None	In urban areas, design public buses well	Use urban public buses everywhere. Increase the

Table 6 *Continued*

#	Adj	Noun	Verb	Adv	New ideas with human sensemaking by a novice	New ideas with human sensemaking by a transportation Researcher A	New ideas with human sensemaking by a transportation researcher B
						enough to eliminate other modes of transportation everywhere	number of buses by a factor of ten and the need for other vehicles will dissolve. Eliminate private car ownership and trains
29	electronic	tunnel	look	always	None	Tunnels can be boring for drivers. We can design electronic LED decoration lights inside the tunnels to make the tunnels look nice and not boring as always	An electronic tunnel dramatically enables AI driving by reducing the need for systems like lidar to always look everywhere
30	free-to-use	commuting	depend	everywhere	Free-to-use commuting is available and fast so that people can leave everywhere even far away from the companies	Free to use commuting service everywhere, made possible by the money made from advertisements	There is a free to use commuting system located everywhere throughout the city
31	shuttle	ups	afford	hard	None	None	Custom shuttle routes can be costly and difficult to plan. This system would enable better shuttle planning through centralizing the controls
32	existing	punch line	operate	immensely	None	None	Using humor, a "punch line" could be developed to make people more aware of problems in public transportation and more willing to change. Use advertising to change mindsets
33	modern	efficient energy use	coordinate	right	None	None	Use modern systems such as AI to make more energy-efficient city level systems
34	fair	United States	ensure	naturally	None	None	The United States should ensure that a fair chance is given to electric vehicles through a "fair pricing" scheme that may involve a large-scale electric charging infrastructure deployment
35	future	mobile phone	track	hard	None	None	It is hard to track mobile phones in the future, due to security systems that mask user's identity. Therefore, traffic planners should explore other systems than relying on google maps/waze as these may not always be available
36	opposite	floor	service	relatively	None	None	The idea is that the opposite flow of traffic is controlled on a city scale, e.g., two major highways become one-way roads depending on the time of day
37	renewable	United States Postal Service	improve	safely	None	Use renewable energy vehicles for USPS deliveries	The US postal service can be one of the first institutions to explore using transportation based entirely on renewable energy. This will pave the

Table 6 *Continued*

#	Adj	Noun	Verb	Adv	New ideas with human sensemaking by a novice	New ideas with human sensemaking by a transportation Researcher A	New ideas with human sensemaking by a transportation researcher B
							way for larger-scale transformations
38	mega	lighting	wind	directly	None	None	While wind farms are relatively efficient, there are large amounts of energy in lighting which are currently not captured, develop a system for powering transport based on capturing the energy in lightning
39	redesigned	parkway	track	together	None	None	A new parkway system enables bicyclists to cluster together and be much more efficient. Like a bicycle train
40	interactive	compressed air	type	around	None	None	Interactive compressed air posts around the city are used to dynamically push commuters around on kite boards. Like wind surfing through downtown
41	tired	Ohio	report	around	None	None	A report is used to explore the causality of exhaustion. This can be used to optimize transportation to enable a better quality of life such as through offset working hours that reduce commute time and thus loss of sleep

Table 7 Count of new keyword combos (standard deviation in parentheses)

	Two-keyword combos	Three-keyword combos	Four-keyword combos
Human	152.00	141.00	39.00
Computer (random coreness)	233.56[a] (0.44)	163.72[a] (0.05)	41.00[a] (0.00)
Computer (top 10–50% coreness)	232.77[a] (0.38)	163.79[a] (0.06)	40.99[a] (0.01)

[a]$p < 0.01$ (one-tail).

Table 8 Percentage of new keyword combos (%, standard deviation in parentheses)

	Two-keyword combos	Three-keyword combos	Four-keyword combos
Human	61.79	85.98	95.12
Computer (random coreness)	94.94[a] (1.77)	99.83[a] (0.30)	100.00[a] (0.00)
Computer (top 10–50% coreness)	94.62[a] (1.54)	99.87[a] (0.35)	100.00[a] (0.25)

[a]$p < 0.01$ (one tail).

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